

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

HANWHA SOLUTIONS CORPORATION,
Petitioner

v.

MAXEON SOLAR PTE. LTD.,
Patent Owner

Case IPR2024-01198
U.S. Patent No. 11,251,315

**DECLARATION OF DAVID L. CARROLL, PH.D. IN SUPPORT OF
PATENT OWNER PRELIMINARY RESPONSE**

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Maxeon EX2001
Hanwha v. Maxeon
IPR2024-01198

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I. INTRODUCTION

1. I submit this declaration in support of the preliminary response submitted by Maxeon Solar Pte. Ltd. (“Maxeon” or “Patent Owner”) in connection with the Petition for *Inter Partes* Review of U.S. Patent No. 11,251,315 (“the ’315 patent”) filed by Hanwha Solutions Corporation’s (“Hanwha”).

2. I am not an employee of Maxeon or any affiliate of subsidiary thereof.

3. I am being compensated for my work in this matter at my standard rate of \$300/hour. I am also being reimbursed for reasonable and customary expenses associated with my work and testimony in this matter.

4. My compensation is not contingent on the outcome of this matter or the content of my testimony.

5. I understand from Maxeon’s counsel that Hanwha has challenged the validity of claims 10-20 of the ’315 patent (the “Challenged Claims”) based on obviousness under 35 U.S.C. § 103.

6. Accordingly, I have been asked to provide certain opinions relating to the validity of the Challenged Claims. Specifically, I have been asked to provide my opinions regarding (i) the level of ordinary skill in the art to which the ’315 patent pertains; (ii) the scope and content of the prior art; (iii) the differences between the prior art and the Challenged Claims; and (iv) whether a person of

ordinary skill in the art at the time of the claimed invention would have been motivated to combine or modify the prior art to achieve the claimed invention.

7. As set forth in detail below, it is my opinion that the Challenged Claims would not have been obvious based on the proposed combinations in Hanwha's Petition.

8. In preparation of this declaration, I have reviewed the following documents and any other documents cited in this Declaration:

Exhibit	Description
EX1001	U.S. Patent No. 11,251,315 ("the '315 patent")
EX1002	File History of U.S. Patent No. 11,251,315
EX1003	Declaration of Zachary Holman, Ph.D. Regarding U.S. Patent No. 11,251,315
EX1004	Curriculum Vitae of Zachary Holman, Ph.D.
EX1006	U.S. Patent App. Pub. No. 2014/0311567 ("Choi")
EX1007	U.S. Patent No. 8,207,444 ("Cousins")
EX1008	Marvin and Froedge, "Interdigitated Back Contact Silicon Solar Cell Analysis and Design Recommendations for Space Use," AD-A220-414 (Sept. 30, 1989) ("Marvin")
EX1010	Granek et al., "High-Efficiency Back Contact Back-Junction Silicon Solar Cells (2009) (Ph.D. Dissertation, Fraunhofer Institute for Solar Energy Systems ISE) ("Granek")
EX1011	U.S. Patent App. Pub. No. 2013/0240029 ("Smith")
EX1015	Istratov et al., "Gettering in silicon-on-insulator wafers: experimental studies and modelling," Semicond. Sci. Technol. 20: 568–575 (April 2005) ("Istratov")

Exhibit	Description
EX2002	Lamers et al., “Towards 21% Efficient N-CZ IBC based on Screen Printing,” <i>26th European Photovoltaic Solar Energy Conference and Exhibition</i> , (2011) (“Lamers”)
EX2003	Desa et al., “Optimization of p-type Screen Printed Interdigitated Back Contact Silicon Solar Cell with Aluminum Back Surface Field,” <i>International Journal of Engineering & Technology IJET-IJENS</i> , 14(2) (2014) (“Desa”)
EX2004	Pham et al., “Dopant-grading proposal for polysilicon passivating contact in crystalline silicon solar cells,” <i>Journal of Power Sources</i> , 522, 2022. (“Pham”)
EX2005	Procel et al., “Analysis of the Impact of Doping Levels on Performance of Back Contact – Back Junction Solar Cells,” 4 th International Conference on Silicon Photovoltaics, SiliconPV 2014, Italy, 2014, pp 128-132, ScienceDirect (“Procel”)
EX2016	“Nanotechnology improves solar cell efficiency,” <i>EarthSky</i> , August 28, 2007 (accessible at https://earthsky.org/human-world/nanotechnology-improves-solar-cell-efficiency ; last accessed October 14, 2024)
EX2017	“New Plastic Solar Cell Breaks Efficiency Record,” <i>ScienceDaily</i> , April 20, 2007 (accessible at https://www.sciencedaily.com/releases/2007/04/070419140902.htm), last accessed October 14, 2024)
EX2018	Capshaw-Mack, C., “Power Games: Project seeks to improve methods of harnessing solar energy,” <i>Winston-Salem Journal</i> , August 4, 2013 (accessible at https://journalnow.com/news/local/article_1d243ff0-fc9e-11e2-b607-001a4bcf6878.html ; last accessed October 15, 2024)

9. In forming the opinions expressed below, I have considered the documents listed above and my own knowledge and experience in the field of solar cell technology, as described below.

II. QUALIFICATIONS AND PROFESSIONAL EXPERIENCE

10. My complete qualifications and professional experience are described in my Curriculum Vitae (“CV”), a copy of which can be found at Appendix A. The following is a brief summary of my relevant qualifications and professional experience.

11. In 1985, I received my Bachelor of Science degree in Physics from North Carolina State University (“N.C. State”). In 1993, I received my Ph.D. in Physics from Wesleyan University. My dissertation was titled *Defect Formation and Electron Trapping in Oxides* and comprised a study on the dynamic energy redistribution and statistics of charged defects in oxide materials.

12. I am currently a Professor in the Department of Physics at Wake Forest University and also serve as an Adjunct Associate Professor of Biomedical Engineering at the Virginia Tech – Wake Forest University School of Biomedical Engineering and Sciences, and as an Adjunct Associate Professor of Cancer Biology at the Wake Forest School of Medicine. From 2003 to 2010, I was an Associate Professor in the Department of Physics at Wake Forest University and

was a Director of the Center for Nanotechnology and Molecular Materials, during which time I was awarded tenure.

13. From 2002 to 2003, I was as an Associate Professor of Materials Science in the Department of Physics and Astronomy at Clemson University. In the same University, I was a tenured Associate Professor of Physics from 2001 to 2002, and an Assistant Professor of Physics from 1997 to 2001.

14. From 1995 to 1997, I served as a research associate at the Max-Planck-Institut für Metallforschung, Institut für Werkstoffwissenschaft, in Stuttgart, Germany. In 1994 and a part of 1995, I served as a Postdoctoral Research Associate in the Department of Materials Science and Engineering at the University of Pennsylvania.

15. At Wesleyan University, I served as an observational astronomer in the Van Vleck Observatories from 1987 to 1989, and as a graduate and research assistant in the Department of Physics from 1987 to 1992.

16. Beyond my academic experience, I have significant professional experience in the fields of physics, materials science, and solar technology. In 2001, I helped found Tetramer Technologies, an advanced materials company dedicated to the development of market-driven materials and transitioning those materials from the lab to the market, and served as a technical advisor and board member from 2001 to 2003. I also helped found and served in the same positions at

NanoTechLabs, a nanomaterial and nanocomposite application development company, from 2001-2004; PureLux, a nanotechnology lighting company, from 2007 to 2011; FiberCell, a laboratory-scale hollow fiber solar cell company, from 2007 to 2010; and Camel City Solar, a spin-out solar cell company from the Wake Forest Nanotechnology Center, from 2011 to 2013. I also served as a technical advisor at CeeLite, a clean technology lighting company, from 2011 to 2013, and VF Corporation, one of the world's largest apparel, footwear, and accessories companies, from 2013 to 2019. In 2022, I helped found Quoherent, a cutting-edge startup pioneering the next frontier in quantum computing, and have since served as a technical advisor.

17. I have received a number of awards and honors for my academic and professional accomplishments, including being named as a Fellow of the American Physical Society in 2013 and the International Association of Advanced Materials (Europe) in 2024. A complete a list of my awards and honors can be found in Section 2 of my CV.

18. I have authored several books and book chapters and my work has been published in nearly 300 publications since 1990, including numerous publications on my work with solar cell technologies. A complete list of my publications and publication metrics are listed in Sections 3.1 to 3.3 of my CV.

19. I am an inventor on 35 issued U.S. patents, including many patents related to solar cell technologies and several patents related to Silicon solar cell technologies. A complete list of my patents can be found in Section 3.4 of my CV.

20. I have received over \$29 million in research grants from various federal and industrial funding sources, including over \$2,500,000 in research grants related to my work with solar cell technologies from the Department of Energy (DOE) and the Air Force Office of Scientific Research (AFOSR). A complete list of my significant research grants can be found in Section 3.5 of my CV.

21. I have presented my work at numerous scholarly conferences, including my work with solar cell technologies. A complete list of my scholarly presentations can be found in Section 3.6 of my CV.

22. My work with solar cell technologies has also been recognized by various publications, including EarthSky, ScienceDaily, and the Winston-Salem Journal. EX2016; EX2017; EX2018.

III. LEGAL STANDARDS

23. I understand that in *inter partes* review proceedings, a patent claim is construed using the same standard that would be used in a civil action, and that a claim should be construed in accordance with the ordinary and customary meaning

of the claim as it would be understood by a person of ordinary skill in the art (“POSITA”).

24. While I am neither a patent lawyer nor an expert in patent law, I have been informed of the applicable legal standards for obviousness. I have relied upon these legal principles, as explained to me by counsel, in forming my opinions set forth in this Declaration.

25. I understand that a patent may be deemed invalid based on obviousness over the prior art. My understanding of this basis for invalidity is discussed in greater detail below.

26. In addition, I understand that objective evidence of non-obviousness such as (i) commercial success, (ii) long-felt but unresolved need, (iii) failure of others, (iv) skepticism by experts, and (v) unexpected results should also be considered in determining whether a claim would have been obvious, if relevant.

27. I understand that in undertaking an invalidity analysis, the claims are to be interpreted from the perspective of a POSITA.

A. Person of Ordinary Skill in the Art

28. I am informed and understand that patent claims are interpreted from the perspective of a person of ordinary skill in the art (“POSITA”) at the time of the invention.

29. I understand that a POSITA is a hypothetical person who is presumed to have known the relevant art at the time of the invention. Such a hypothetical person would have the capability of understanding the scientific and engineering principles applicable to the pertinent art of the claimed invention. Factors that may be considered in determining the level of ordinary skill in the art include: (A) the type of problems encountered in the art; (B) prior art solutions to those problems; (C) rapidity with which innovations are made; (D) sophistication of the technology; and (E) educational level of active workers in the field.

30. The '315 patent generally relates to a TOPCon solar cell—a solar cell with a silicon substrate, a dielectric region formed over the back side of the silicon substrate, an emitter region over the dielectric region, and a metal contact formed over the emitter region. I understand that Hanwha and Hanwha's declarant, Dr. Zachary Holman, state that "[a] POSITA at the earliest alleged priority date (December 22, 2014) would have had (1) an advanced degree in electrical engineering, mechanical engineering, applied physics, chemistry, materials science, or a related discipline and (2) at least one year of experience designing, developing, or researching the design and/or manufacture of solar cells or related technologies." Pet., 23; EX1003, ¶39. Hanwha and Dr. Holman also assert that, "[a]lternatively, a POSITA would have had (1) a bachelor's degree in one of the aforementioned disciplines and (2) at least two years of experience designing,

developing, or researching the design and/or manufacture of solar cells or related technologies” and that less work experience may be compensated for by a higher level of education, and vice versa. Pet., 23-24; EX1003, ¶39.

31. For the purposes of this Declaration, I apply Hanwha’s level of ordinary skill. Further, I possessed at least such experience and knowledge at the relevant time frame for the ’315 patent, and my opinions apply equally under either proposed level of ordinary skill. I will therefore apply the same definition in this declaration.

B. Obviousness

32. I have been informed that a patent claim is invalid as being obvious in view of the prior art if the differences between the patented subject matter and the prior art are such that the subject matter as a whole would have been obvious at the time of the invention to a person having ordinary skill in the art. In making a determination of obviousness, I understand that the following factors are analyzed: (i) the scope and content of the prior art; (ii) the differences, if any, between the prior art and the claims at issue; (iii) the level of ordinary skill in the pertinent art; and (iv) objective evidence of non-obviousness, if any exists.

33. I have been informed that any of the following rationales are some of the acceptable bases for the conclusion that a claim is obvious: (i) the claimed invention is simply a combination of prior art elements according to known

methods to yield predictable results; (ii) the claimed invention is a simple substitution of one known element for another to obtain predictable results; (iii) the claimed invention uses known techniques to improve similar devices (methods, or products) in the same way; (iv) the claimed invention was “obvious to try” because it was a choice from a finite number of identified, predictable solutions, with a reasonable expectation of success; (v) there is known work in one field of endeavor that may prompt variations of it for use in either the same field or a different one based on design incentives or other market forces, if the variations would have been predictable to a POSITA; or (vi) there is some teaching, suggestion, or motivation in the prior art that would have led a POSITA to modify the prior art references or to combine prior art reference teachings to arrive at the claimed invention.

34. I have been informed that in order for a patent claim to be considered obvious, at the time the invention was made, each and every limitation of the claim must be present within the prior art, or within the prior art in combination with the general knowledge held by a POSITA, and that such a person would have a reasonable expectation of success in combining these teachings to achieve the claimed invention. I also understand that the reason to select and combine features, the predictability of the results of doing so, and a reasonable expectation of success of doing so may be found in the teachings of the prior art themselves, in the nature

of any need or problem in the field that was addressed by the patent, in the knowledge of a POSITA in the field at the time, as well as in common sense or the level of creativity exhibited by a POSITA. There need not be an express or explicit suggestion to combine references.

35. I understand that substituting one known element for another known element would have been obvious when it leads to reasonably predictable results.

36. I understand that a combination of elements would have been obvious when a POSITA has a good reason to pursue the combination, which is among a finite number of known options within his or her technical grasp, and leads to reasonably expected results.

37. A prior art reference can be said to teach away when a POSITA would be discouraged from following the path set out in the reference or would be led in a direction divergent from the path that was taken in the claimed invention. The mere disclosure of more than one alternative does not constitute a teaching away from alternatives that are not disclosed when the prior art does not criticize, discredit, or otherwise discourage the solution claimed in the alleged invention. Similarly, a prior art reference that merely expresses a general preference for an alternative invention does not teach away.

38. I have relied upon this understanding of the applicable legal standards in reaching my opinion set forth in this Declaration.

IV. OVERVIEW OF THE '315 PATENT

A. The '315 Patent

39. The '315 patent discloses “solar cell fabrication techniques to improve solar cell lifetime, passivation and/or efficiency” (EX1001, 3:17-21) in tunnel oxide passivated contact (“TOPCon”) solar cell configurations.¹ “Efficiency is an important characteristic of a solar cell as it is directly related to the solar cell’s capability to generate power.” EX1001, 1:35-37. As explained below, charge carrier lifetime and surface passivation are inter-related characteristics, in which improving one has the potential to negatively impact the other or increase the cost and complexity of the solar cell. But the solar cell covered by the Challenged Claims provides for improvements in *both* of these performance characteristics *and* a boost in solar cell efficiency, while controlling the number of manufacturing steps to minimize or optimize the manufacturing cost of the solar cell.

40. The “lifetime” of charge carriers in a solar cell refers to the average time that electrons and holes can exist before recombining. The longer the charge

¹ While the TOPCon moniker was not coined until 2013 by researchers at the Fraunhofer Institute for Solar Energy Systems, SunPower had been developing and optimizing solar cells employing tunnel oxide layers between the silicon substrate and doped polysilicon regions prior to 2013.

carriers can remain separate, the greater the chance they have to reach the electrical contacts of the solar cell and contribute to the current output, thus increasing the solar cell's efficiency. Accordingly, a “[h]igher lifetime is preferred for high efficiency solar cells.” EX1001, 9:35-36. Neuhaus and Munzer, *Industrial Silicon Wafer Solar Cells*, Advances in OptoElectronics, 1-15, at 11 (2007) (“Neuhaus”), discloses that to improve the lifetime of charge carriers, manufacturers often use high-quality, pure semiconductor materials and carefully control the manufacturing process to reduce defects within the crystal lattice. EX1084, 11 (“SunPower is using wafers with lifetimes greater than 1 millisecond.”). These defects can act as recombination centers where electrons and holes prematurely recombine, reducing the lifetime of charge carriers. These higher-grade materials and more stringent manufacturing controls, however, increase costs.²

41. “Surface passivation” involves the treatment of a solar cell's surface to reduce the number of recombination sites available. This is typically achieved by creating a thin insulating layer (such as silicon nitride or aluminum oxide) on the surface of the semiconductor material, which can prevent charge carriers from

² Additionally, the processes used to improve lifetime, such as thermal treatments, can introduce other challenges, such as increased stress within the solar cell, which can affect its mechanical stability.

recombining at the surface. The '315 patent states that “[l]ower surface passivation is preferred for high efficiency solar cells.” EX1001, 9:27-28. The deposition of passivation layers requires additional steps in the production process, which can increase the time and resources needed to manufacture solar cells. Moreover, if not carefully optimized, the passivation layer can introduce electronic defects or impede the collection of charge carriers, potentially reducing the overall efficiency or preventing one from achieving optimized conditions.

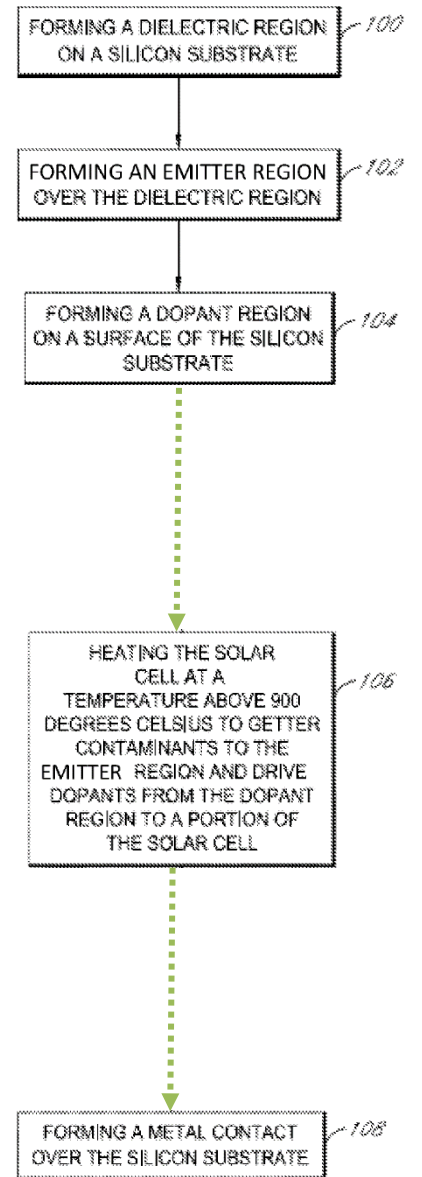
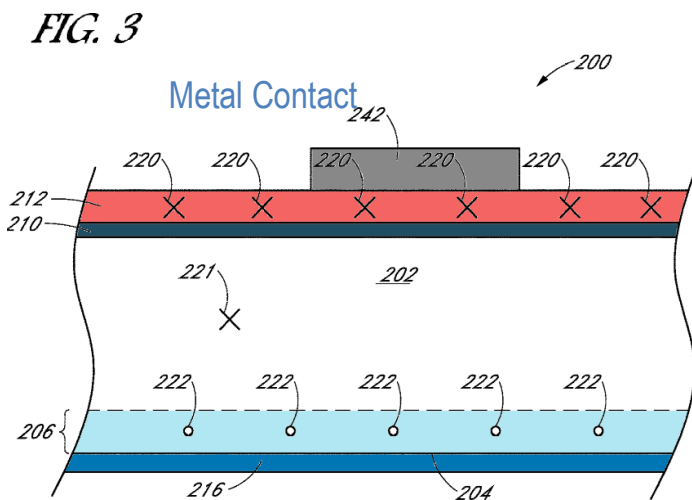
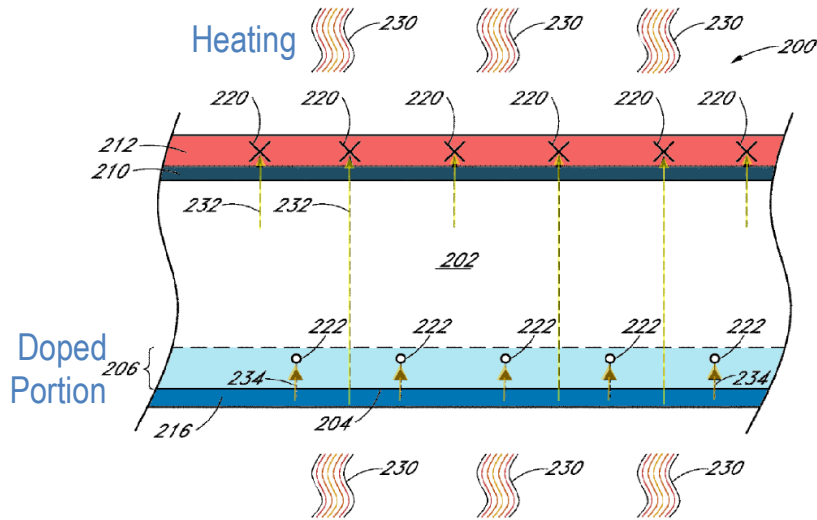
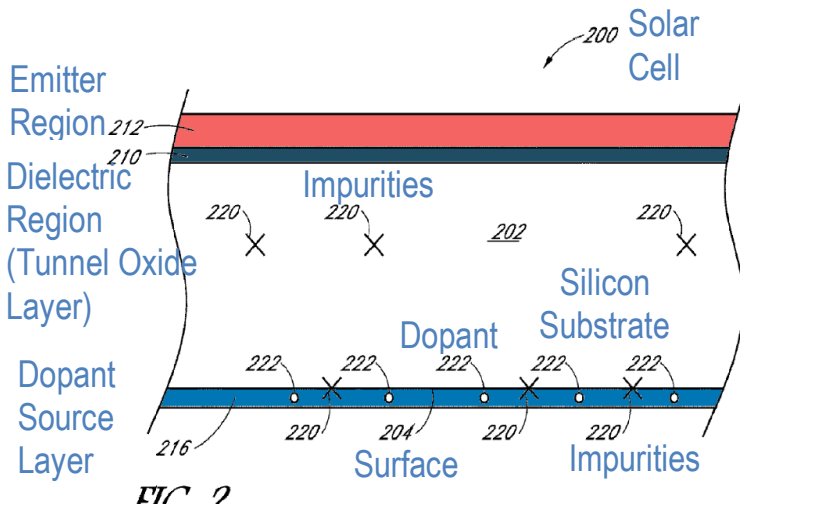
B. The '315 Patent's Novel Solar Cell Fabrication Technique

42. The '315 patent discloses a solar cell fabricated by (1) forming a dielectric region (e.g., a tunnel oxide layer) over a silicon substrate, (2) forming an emitter region over the dielectric region, (3) forming a dopant region (e.g., a dopant source layer) on a surface of the silicon substrate, and (4) heating the solar

cell above 900 degrees Celsius such that the surface of the solar cell is doped to a concentration of less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$ and the emitter region contains contaminants gettered from the silicon substrate through the dielectric region.

These fabrication steps are illustrated in Figures 1-4 (annotated below).³

³ Throughout its Petition, Hanwha and Dr. Holman allege that the solar cell design disclosed in the '315 patent is a “back-contact solar cell” to draw comparisons with the asserted references. However, the '315 patent is not limited to a “back contact solar cell.” EX1001, 7:13-14. In fact, independent claims 1 and 10 require only a single emitter region and contact (e.g., a first emitter region and a first metal contact). For claim 1, the emitter and metal contact are on the front side of the solar cell, and, for claim 10, they are on the back side. Dependent claim 20 is the first limitation that requires both “P-type” and “N-type doped polysilicon region[s]” formed on the back side of the solar cell, which is a “back contact solar cell” configuration.



EX1001, FIGs. 1-4 (annotated).

43. The '315 patent explains (and summarizes in Figure 11) that this particular combination of steps to form a solar cell provided increased efficiency that was both unique and unexpected. Figure 11 shows four processes where the heating temperature and surface dopant concentrations were varied and the gettering location, surface passivation, lifetime, and efficiency results were measured.⁴ EX1001, Figure 11 (below, color annotations added).

⁴ I agree that an inadvertent error was made in Figure 11 that shows all the temperature settings to be less than or equal to 900 degrees Celsius. Pet., 21, n.3. The original application included the same information as Table 1 in the specification, which was later amended to be Figure 11. EX1002, 43. Table 1 in the original application correctly shows that the Example Processes C and D in Figure 11 should have temperature settings at *greater than* 900 degrees Celsius as described in the text. EX1002, 43.

Variables			Results			
Example Process	Temp	Surface Dopant Conc.	Gettering Location	Surface Passivation	Lifetime	Efficiency
A	≤ 900 deg-C	$2 \times 10^{18} \text{ cm}^{-3}$	non-poly	2 fA/cm^2	$\sim 3 \text{ msec}$	Baseline
B	≤ 900 deg-C	$4 \times 10^{18} \text{ cm}^{-3}$	non-poly	5 fA/cm^2	$\sim 10 \text{ msec}$	Baseline
> 900 deg-C C	≤ 900 deg-C	$2 \times 10^{18} \text{ cm}^{-3}$	poly	2 fA/cm^2	$\sim 10 \text{ msec}$	+0.5 % abs.
> 900 deg-C D	≤ 900 deg-C	$4 \times 10^{18} \text{ cm}^{-3}$	poly	5 fA/cm^2	$\sim 10 \text{ msec}$	Baseline

Table 1. Example Processes for Solar Cell Fabrication

FIG. 11

EX1001, FIG. 1 (annotated).

44. In Example Process A, low temperature (e.g., ≤ 900 degrees Celsius) heating and low surface dopant concentration (e.g., $2 \times 10^{18} \text{ cm}^{-3}$) were used. The '315 patent explains that "[o]xides and/or tunnel oxides, such as the dielectric region . . . , can be barriers to gettering of the metal impurities 220 to emitter regions" and that "heating at temperature at 900 degrees Celsius or below can be insufficient to diffuse metal impurities through a tunnel oxide and into a polysilicon region." EX1001, 5:15-20. Accordingly, the "Gettering Location" for Example Process A is the "non-poly" silicon substrate, rather than the "poly" emitter region. The combination of low temperature gettering and low surface dopant concentration allows for good surface passivation, but poor lifetime.

45. Example Process B also uses low temperature heating, but a higher surface dopant concentration (e.g., $4 \times 10^{18} \text{ cm}^{-3}$). Like Example Process A, the gettering location remains in the “non-poly” silicon substrate. The low temperature gettering and higher surface dopant concentration results in a good lifetime, but poor surface passivation. Example Processes A and B demonstrate the kind of trade-offs that are made when designing solar cells. Having a low surface dopant concentration results in good surface passivation, but poor lifetime; whereas a high surface dopant concentration results in good lifetime, but poor surface passivation. For both processes, the efficiency of the solar cell remained the same.

46. The unexpected result came from Example Process C, where high-temperature (e.g., > 900 degrees Celsius) heating and low surface dopant concentration are used. In this process, contaminants from the silicon substrate getter through the dielectric region and into the “poly” emitter region. At the same time, dopants are driven deeper into the silicon substrate from the surface of the silicon substrate resulting in a lower surface dopant concentration. At the time of the invention, it was not known whether high-temperature heating would getter contaminants through the dielectric region, while leaving this region intact and functional, or whether there would be some split between contaminants gettered between the surface of the “non-poly” silicon substrate and the “poly” emitter region, such that lifetime would not show any improvement (which was the case

for Example Process D, described below). Further, a POSITA would not have expected lifetime to improve by high-temperature heating because the silicon substrate also contains oxygen defects, which would be enlarged at higher temperatures and increase the likelihood of Ingot Ring Defects (IRD), which would reduce lifetime. Example Process C, however, provided both improved surface passivation and lifetime, resulting in a 0.5% increase in efficiency over the other example processes.

47. Example Process D also produced an unexpected result in that high-temperature (e.g., > 900 degrees Celsius) heating did not further improve the lifetime beyond what a high surface dopant concentration already produced in a TOPCon solar cell configuration (e.g., Example Process B). Thus, Example Process D demonstrates that a high-temperature heating step alone does not yield improved efficiency in the claimed solar cell configuration unless the surface dopant concentration is low. In other words, the '315 patent requires a specific combination of fabrication steps and surface dopant concentration to improve the performance of a particular solar cell structure.

C. The '315 Patent Prosecution History

48. It is my understanding that the Examiner agreed that the claimed invention was patentable:

4. The following is an examiner's statement of reasons for allowance: Claims **1 – 20** are allowable over the prior art of record because none of the prior art whether taken singularly or in combination, especially when these limitations are considered within the specific combination claimed, to teach:

portion of the silicon substrate is formed at the back side of the solar cell and a first dielectric region formed over the silicon substrate, wherein the first dielectric region is formed over the front side of solar as recited in the independent claim **1**; and portion of the silicon substrate is formed at the front side of the solar cell; a dielectric region formed over the silicon substrate, wherein the dielectric region is formed over the back side of solar; a first emitter region having metal impurities formed over the dielectric region as recited in the independent claim **10**.

EX1002, 207.

49. While the Examiner allowed these claims without issuing any rejections, I note that a significant number of references cited during prosecution resulted from previous searches in related patents.

50. It is my understanding that Hanwha's petition asserts three grounds of unpatentability against the Challenged Claims. Pet., 7. In my opinion, Hanwha not does show that it would have been obvious to a POSITA to combine the primary reference, Choi or Cousins, with the secondary reference, Granek or Marvin, to teach or suggest the claimed "dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$ " of independent claim 10. Also, it is my opinion that Hanwha does not show that it would have been obvious to a POSITA to combine the primary reference, Choi or Cousins, with the secondary reference, Istratov, to teach or suggest the claimed "first emitter region having metal impurities formed over

the dielectric region” of independent claim 10. Additionally, in my opinion, Hanwha not does show that it would have been obvious to a POSITA to combine the primary reference, Choi, with the secondary reference, Istratov, to teach or suggest the claimed “second emitter region having metal impurities formed over the dielectric region” of dependent claim 16, which I understand depends from independent claim 10 and also incorporates the limitations of claim 10. Further, in my opinion, Hanwha not does show that it would have been obvious to a POSITA to combine the primary reference, Choi, with the secondary reference, Smith, to teach or suggest the claimed “trench region” of dependent claim 18, which I understand depends from claim 16 and also incorporates the limitations of claims 10 and 16.

V. ALL GROUNDS: HANWHA AND DR. HOLMAN DO NOT SHOW THAT THE PRIOR ART COMBINATIONS TEACH OR SUGGEST THE CLAIMED “DOPANT CONCENTRATION.”

51. Both Hanwha and Dr. Holman rely on outdated and incompatible solar cell configurations of Granek (EX1010) and Marvin (EX1008) to teach the claimed “dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$.” In addition, both Hanwha and Dr. Holman ignore Granek’s and Marvin’s teachings of solar cell structures as a whole and selectively pick their dopant concentration recommendations to teach the claimed “dopant concentration.” Moreover, Hanwha and Dr. Holman do not show why a POSITA would have been

motivated to implement Granek's or Marvin's dopant concentrations in Choi or Cousins, in view of optimum dopant concentrations—higher than $2 \times 10^{18} \text{ cm}^{-3}$ —for solar cell configurations compatible with Choi and Cousins, such as Lamers (EX2002), Desa (EX2003), and Procel (EX2005).

A. Grounds I and II: Hanwha and Dr. Holman do not show why a POSITA would have been motivated to combine Choi with Granek or Marvin.

52. In my opinion, Hanwha and Dr. Holman do not show that a POSITA would have been motivated to combine Choi with Granek or Marvin to teach the claimed “dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$.” In particular, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to adopt Granek's three-layer passivation solar cell teachings for improving Choi's two-layer passivation solar cell structure and adopt Marvin's outdated solar cell teachings—with known disadvantages—for improving Choi's solar cell structure.

1. A POSITA would not have adopted Granek's three-layer passivation solar cell teachings for improving Choi's two-layer passivation solar cell structure.

53. Hanwha argues that “[a] POSITA would have been motivated to use Granek's ... dopant concentration in Choi's FSF region.” Pet., 36. Similarly, Dr. Holman argues that “a person of ordinary skill in the art would have been motivated to implement a FSF dopant concentration of approximately $1 \times 10^{18} \text{ cm}^{-3}$

and $1 \times 10^{17} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$ as disclosed in Granek and Marvin, respectively, in Choi's front surface field region." EX1003, ¶184. But, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to look to Granek's three-layer surface passivation structure, which is structurally different from Choi's two-layer surface passivation structure to determine a front surface dopant concentration in Choi. In my opinion, Hanwha ignores these structural differences and wrongly asserts that "Choi [and] Granek ... each teach solar cells with similar structures" and "[a] POSITA would have recognized that the dopant concentrations taught by Granek ... would have equal application to Choi and would have been motivated to use those concentrations to reduce recombination, thereby improving efficiency." Pet., 38, 40. Similarly, Dr. Holman ignores these structural differences when wrongly asserting that "given the similarities among the references, a person of ordinary skill in the art would have been able to achieve an improved efficiency solar cell using the dopant concentrations disclosed by Granek and Marvin." EX1003, ¶197. As I explain below in this Section, both Hanwha's and Dr. Holman's assertions are solely based on a selective, incorrect reading of Granek's front surface dopant concentration to teach the claimed "dopant concentration," while ignoring the teachings of Granek's surface passivation structure as a whole. Also, in my opinion, both Hanwha and Dr. Holman ignore the teachings of references, such as Lamers and Desa, with surface passivation structures that are

similar to Choi's surface passivation structures. Both Lamers and Desa disclose optimum dopant concentrations for highly-efficient solar cells higher than the claimed "dopant concentration of approximately less than or equal to 2×10^{18} cm⁻³."

- a. **Hanwha and Dr. Holman ignore the impact of Granek's stack system of silicon nitride/silicon oxide passivation layers—a structure missing in Choi's solar cell—in combination with Granek's front surface dopant concentration on solar cell efficiency.**

54. In my opinion, Hanwha and Dr. Holman ignore the surface passivation structure differences between Choi and Granek, when Hanwha asserts that:

a POSITA would have known that fabricating Choi's cell with Granek's [] dopant concentrations would have involved a minor adjustment to one fabrication step.... [O]nly minor adjustments to the processing parameters of the dopant-diffusion process (such as heating time and temperature) would be required. No other steps would be affected, and no additional steps would be needed.

and when Dr. Holman asserts that:

it is my opinion that only minor adjustments to the solar cell fabrication process would be required to make the solar cell of Choi with the dopant concentrations taught by Granek and Marvin.... [O]nly a small adjustment would be required to dope the front surface field at these concentrations, and a person of ordinary skill in the art would have known how to adjust the dopant concentration. For example, the heating time and temperature during the dopant diffusion

process would need to be changed, but no additional processing steps or adjustments would be necessary. Furthermore, no other existing processing steps would be affected.

Pet., 41; EX1003, ¶199.

55. Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to adopt only Granek's dopant concentration of the front surface field (FSF) layer to improve Choi's solar cell efficiency, without adopting parameters of the stack system of $\text{SiO}_2/\text{SiN}_x$ passivation layers in Granek's surface passivation structure. As I explain below in this Section, Granek demonstrates that its solar cell efficiency depends on both the parameters of its FSF layer (e.g., doping profile and dopant concentrations) and the parameters of its stack system of $\text{SiO}_2/\text{SiN}_x$ passivation layers (e.g., thickness). EX1010, 123, 129.

56. Granek discloses a solar cell with a three-layer surface passivation structure on its front side surface. Referring to Figure 4-1 (reproduced and annotated below), Granek's three-layer surface passivation structure includes an anti-reflective (AR) silicon nitride (SiN_x) layer (highlighted blue), a silicon oxide (SiO_2) layer (highlighted yellow) under the SiN_x layer, and a front surface field (FSF) layer (highlighted red) under the SiO_2 layer, for front surface passivation of the front side surface of Granek's solar cell. EX1010, 45-46, 119-120. Granek explains that its three-layer surface passivation structure "reduce[s] the recombination rate at the [front side] silicon surface" of its solar cell. EX1010,

119. The SiN_x layer and the SiO_2 layer “are applied in the investigated solar cell structure in a form of a stack of passivation layers” to “reduce the density of the surface states” on the front side surface of Granek’s solar cell. EX1010, 119. And, the FSF layer is used to “passivate[] the silicon surface by a strong reduction of holes concentration at the surface.” EX1010, 45-46, 119.

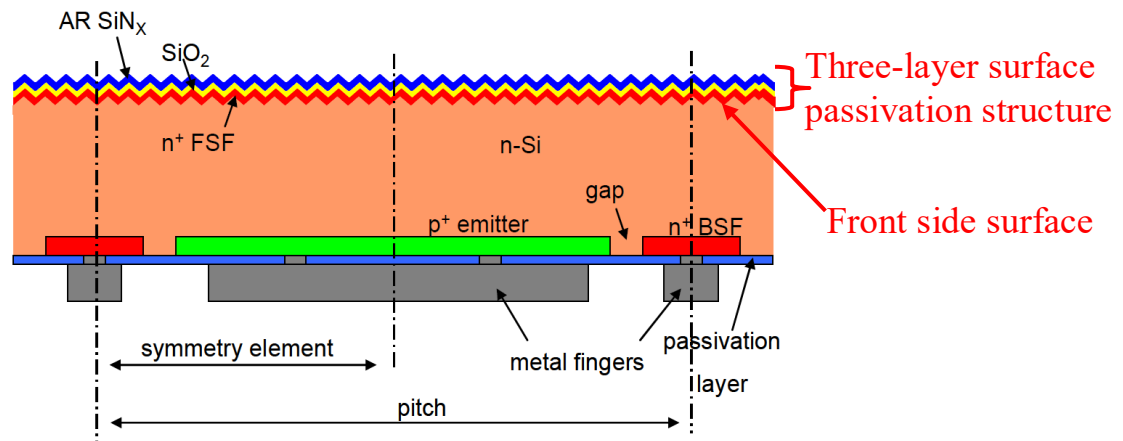


Figure 4-1 Schematic cross-section of the n-type high-efficiency back-contact back-junction silicon solar cell developed in the frame of this thesis (sketch is not to scale). Pitch and symmetry element are shown.

EX1010, FIG. 4-1 (annotated).

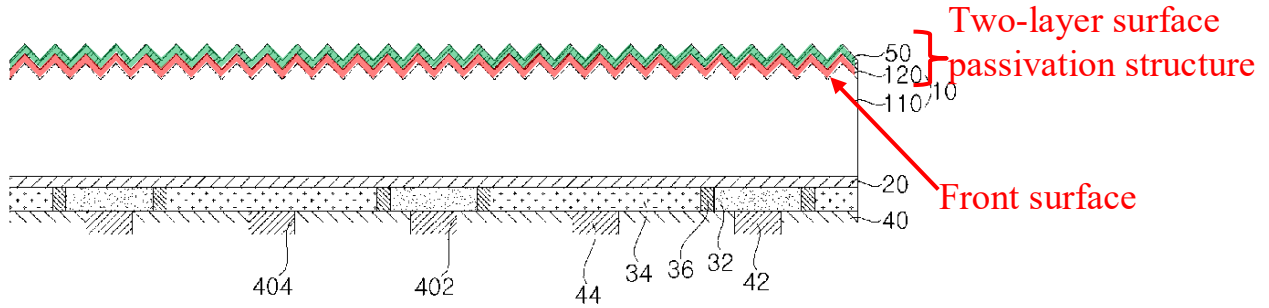
57. Granek analyzes “the front surface passivation quality of the phosphorus doped [FSF layer] combined with [the] stack system of $\text{SiO}_2/\text{SiN}_x$ passivation layers” to determine the dopant concentration of the FSF layer in correlation to the stack system of $\text{SiO}_2/\text{SiN}_x$ passivation layers for the highest solar efficiency. EX1010, 119-120. Granek concludes that “for the poorly passivated surfaces, highly doped and deep diffusion profiles are optimal in order to minimize the surface recombination [], with sheet resistance of about $10 \Omega/\text{sq}$. On the other hand, for the well passivated surfaces, an optimal diffusion profile is lowly doped

and shallow [], with the sheet resistance of around 200 to 800 Ω /sq.” EX1010,

123. Granek further concludes that “a good surface passivation with thin SiO₂ and antireflection SiN_x layers have enabled processing of back-junction back-contact solar cells with efficiencies greater than 21%” EX1010, 129.

58. Compared to Granek, Choi does not disclose passivation layers arranged in a stack system of SiO₂/SiN_x passivation layers on its FSF layer. Specifically, Choi does not disclose a SiN_x passivation layer disposed on a SiO₂ layer, which is disposed on its FSF layer. Instead, referring to Figure 1 (reproduced and annotated below), Choi discloses a solar cell 100 with a two-layer surface passivation structure that includes an anti-reflective film 50 (highlighted green) and an FSF layer 120 (highlighted red) on its front surface. EX1006, ¶¶29-30. To reduce the recombination rate at the front surface of Choi’s solar cell, the FSF layer 120 “prevents electrons and holes separated by incident light from being recombined and then decay on the front surface of the semiconductor substrate 10,” and the anti-reflective film 50 “passivates defects present on the surface or in the bulk of the front surface field layer 120.” EX1006, ¶¶29-30. In addition, the anti-reflective film 50 “removes recombination sites of minority carriers and thus increases open-circuit voltage (Voc) of the solar cell 100. As such, the anti-reflective film 50 increases open-circuit voltage and short current of the solar cell 100, thus improving conversion efficiency of the solar cell 100.” EX1006, ¶31.

100



EX1006, FIG. 1 (annotated).

59. Thus, in my opinion, due to the structural differences between the surface passivation structures of Choi and Granek, a POSITA would not have been motivated to adopt Granek's teachings to modify Choi.

b. Hanwha and Dr. Holman do not consider solar cells with surface passivation structures similar to Choi's solar cell.

60. In my opinion, Hanwha and Dr. Holman do not show why a POSITA would have been motivated to modify Choi with Granek despite the structural differences between them. There are other references, such as Lamers and Desa, with surface passivation structures similar to Choi's passivation structure. These other references report optimum dopant concentrations in their FSF layers. As I explain below in this Section, both Lamers and Desa report optimum dopant concentrations for highly-efficient solar cells higher than the claimed "dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$."

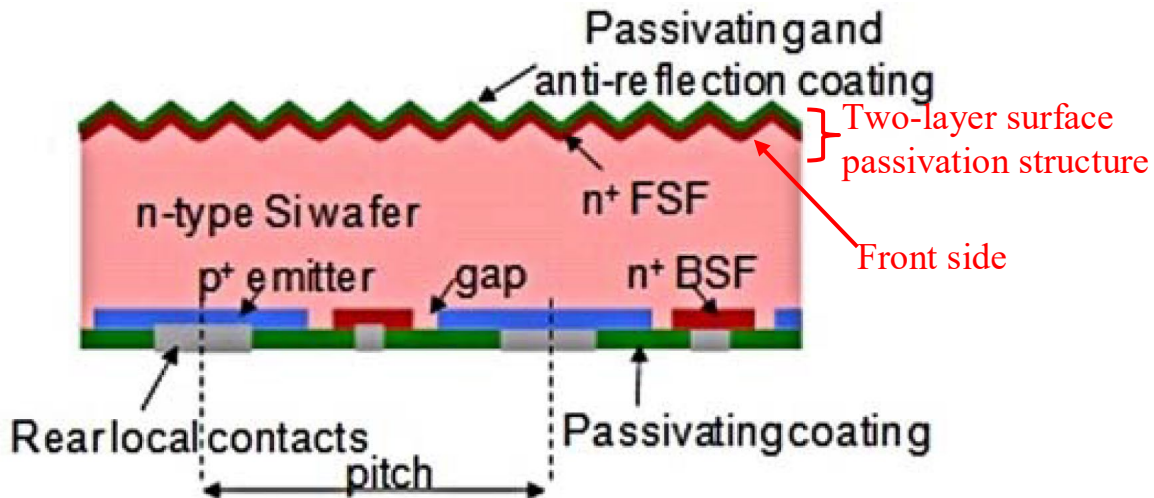
61. Referring to Figure 1 (reproduced and annotated below), Lamers discloses a solar cell with a two-layer surface passivation structure having a

passivation/anti-reflection coating (highlighted green) and an FSF layer (highlighted red) on its front surface. EX2002, 1 (“The front side is passivated using SiNx:H coating on top of the FSF.”). Lamers reports that:

The function of the front surface is to reduce the recombination at the front side and improve lateral transport. Recombination in the FSF should be minimal and the optimal doping level was found to be $3 \cdot 10^{18}$ atoms/cm². ... It can be seen that the Jsc is optimal for dopants at $3 \cdot 10^{18}$ atoms/cm³ for a wide variety of S as it shows that for this doping level the processing is most stable in terms of surface passivation.... Taking note of the increasing required processing time with increasing depth of the FSF and the more optimal process stability for a shallow FSF, it was therefore decided to use a shallow and a high resistance FSF with a surface doping level of $3 \cdot 10^{18}$ atoms/cm³ which had a J_{0e} of 44fA/cm² as measured on textured n-type Cz wafers.

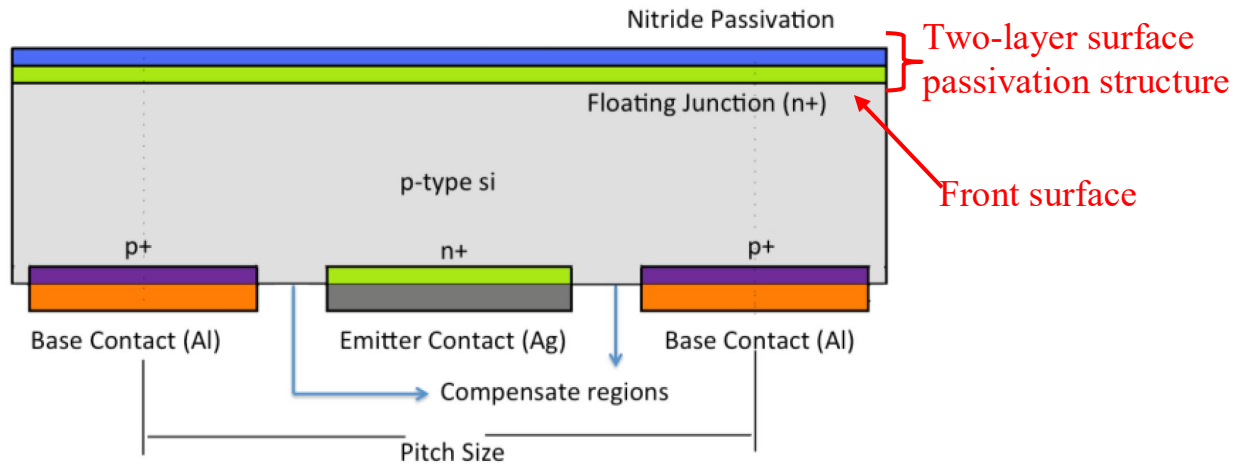
EX2002, 2. In other words, an optimal short circuit current J_{sc} of the solar cell is achieved with an optimum FSF dopant concentration of 3×10^{18} atoms/cm², which is higher than the claimed “dopant concentration of approximately less than or equal to 2×10^{18} cm⁻³.” Lamers further reports solar cell efficiencies above 21%, which is comparable to Granek’s solar cell efficiency (discussed below in Section V.A.1.c) for parameter values obtained for Lamers’s solar cell. EX2002, 3 (“Combining commonly reported FF values of around 79% with the obtained values for Jsc and Voc in this work would result in cell efficiencies well above

21%.”). This solar cell efficiency is reported for dopant concentrations higher than the claimed “dopant concentration.”

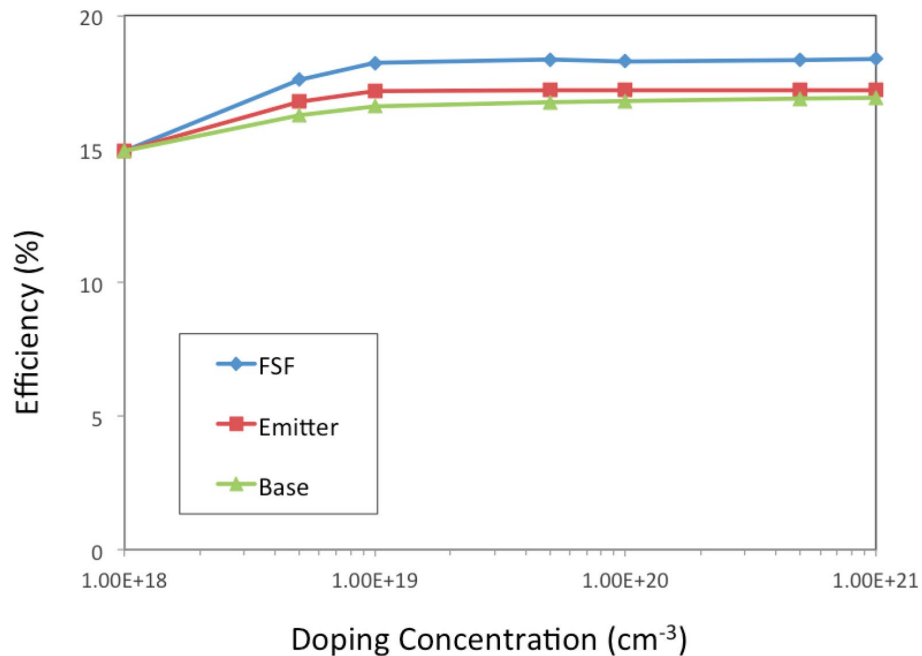


EX2002, FIG. 1 (annotated).

62. Similarly, referring to Figure 2 (reproduced and annotated below), Desa discloses a solar cell with a two-layer surface passivation structure having a nitride passivation layer (highlighted blue) and an FSF layer (highlighted green) on its front surface. EX2003, 70 (“The emitter or n+ regions and front surface field (FSF) layer (floating junction) were created by phosphorous implantation. ... SiN_x layer was deposited as passivation and anti-reflective coating.”). Based on this two-layer passivation structure, Desa demonstrates (Figure 5c below) the highest solar cell efficiency achieved for a dopant concentration of 10^{19} cm^{-3} in the FSF layer, which is higher than the claimed “dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$.”



EX2003, FIG. 2 (annotated).

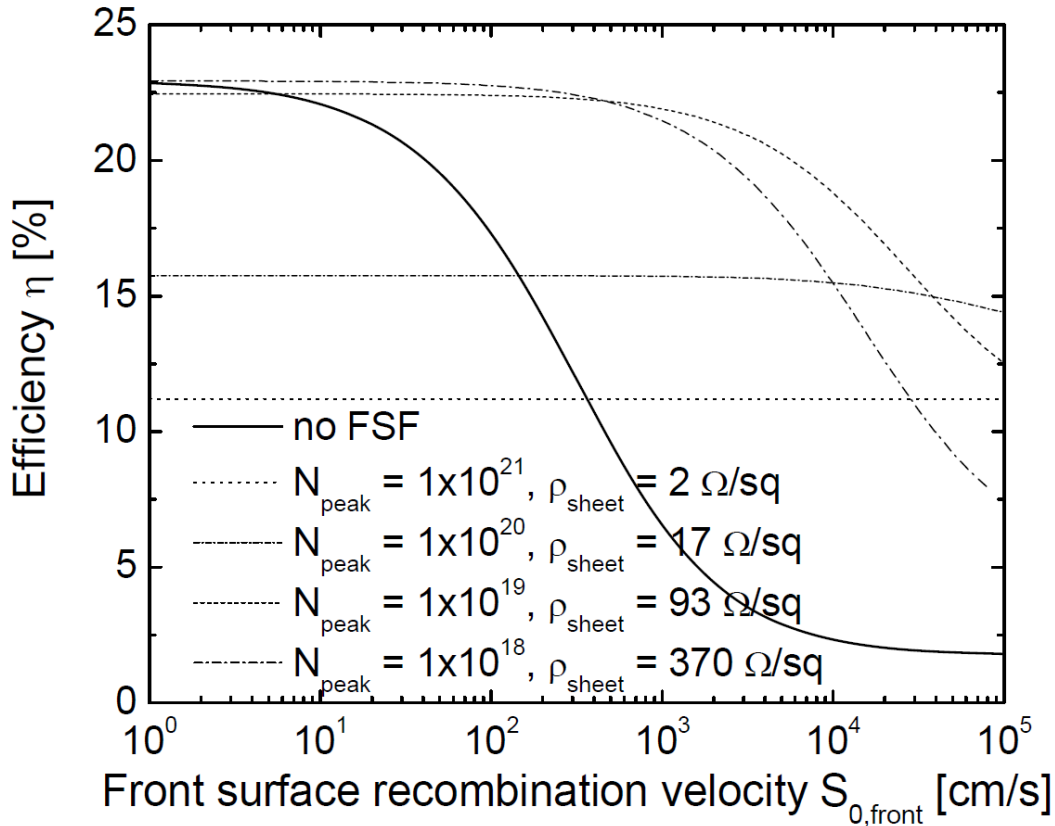


EX2003, FIG. 5c (annotated).

63. Thus, in my opinion, a POSITA would not have been motivated to adopt Granek's teachings to modify Choi when other references, such as Lamers and Desa, report optimum FSF dopant concentrations in their surface passivation structures that are similar to Choi's surface passivation structure.

c. Hanwha and Dr. Holman misinterpret Granek's disclosure to support their motivation to combine rationales.

64. In my opinion, Hanwha and Dr. Holman rely on false statements to support their arguments for combining Choi with Granek. Referring to Figure 7-1 below, both Hanwha and Dr. Holman rely on Granek's simulated highest solar cell efficiency of 23% for a dopant concentration of $1 \times 10^{18}/\text{cm}^3$ of the FSF layer to arrive at the claimed "dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$ " and to show that a POSITA would have been motivated to combine Choi with Granek to improve efficiency. Pet., 37-38 ("Granek discloses that a back-contact solar cell with an FSF dopant concentration of approximately $1 \times 10^{18} \text{ cm}^{-3}$ achieves the highest efficiency. ... [A POSITA] would have been motivated to use those concentrations to reduce recombination, thereby improving efficiency."); EX1003, ¶147 ("As shown in Figure 7-1, the simulated solar cell's efficiency is highest when the FSF dopant concentration is $1 \times 10^{18} \text{ cm}^{-3}$.").



EX1010, FIG. 7-1 (annotated).

65. However, in my opinion, throughout its disclosure, Granek never acknowledges the simulated highest solar cell efficiency as the highest efficiency that can be achieved from its developed solar cells. Rather, Granek relies on experimental values for the highest solar cell efficiencies when describing optimized solar cell parameters. EX1010, 131 (“The highest efficiency of 20.8% was achieved on base resistivity of $1 \Omega \text{ cm}$ and deep diffused FSF (FSF5).”), Abstract (“The highest solar cell efficiency of 21.1% ($J_{SC} = 38.6 \text{ mA/cm}^2$, $V_{OC} = 668 \text{ mV}$, $FF = 82.0\%$) was achieved on $160 \mu\text{m}$ thick $1 \Omega \text{ cm}$ n-type FZ Si with the designated area of 4 cm^2 .”). Granek reports a highest efficiency of 20.8% for a

solar cell with a dopant concentration of $3.8 \times 10^{18}/\text{cm}^3$ of the FSF layer. EX1010, 131-132. Granek also reports a highest efficiency of 20.8% for a laboratory-scale (4 cm^2) solar cell with a dopant concentration of $5 \times 10^{18}/\text{cm}^3$ of the FSF layer. EX1010, 46, 70.

66. In my opinion, because the dopant concentrations of the FSF layer related to the experimental values of the highest solar cell efficiencies are higher than the claimed “dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$,” Hanwha attempts to reconcile this disparity between the simulated and experimental values by wrongly concluding that “[a] POSITA would have expected, based on Granek’s experiments, that further decreasing the concentration to approach the simulation result of $1.0 \times 10^{18}/\text{cm}^3$ would have further improved performance.” Pet, 40, n.5. Similarly, Dr. Holman wrongly concludes: “a person of ordinary skill in the art, looking at both Granek’s simulation results and experimental results in conjunction, would have expected that a FSF dopant concentration of about $1.0 \times 10^{18} \text{ cm}^{-3}$ would have achieved a higher efficiency.” EX1003, ¶153.

67. In my opinion, these statements by Hanwha and Dr. Holman are contradicted by Granek itself. Granek discloses that a highest efficiency of 20.8% was achieved for a solar cell with a dopant concentration of $3.8 \times 10^{18}/\text{cm}^3$ of the FSF layer. EX1010, 131-132. Granek also discloses a laboratory-scale (4 cm^2)

solar cell with a dopant concentration of $5 \times 10^{18}/\text{cm}^3$ of the FSF layer, for which a “best conversion efficiency of 21.1% (designated area measurement) was achieved on $1 \Omega \text{ cm}$ n-type FZ Si with the pitch of $2200 \mu\text{m}$.” EX1010, 46, 70. Thus, an increase in solar efficiency—from 20.8% to 21.1%—was observed with an increase in dopant concentration of the FSF layer. In my opinion, this increasing trend in solar efficiency based on increasing dopant concentration directly contradicts Hanwha’s and Dr. Holman’s positions that decreasing dopant concentration improves solar cell performance.

68. Moreover, in my opinion, even if a POSITA would have been motivated to modify Choi with Granek’s dopant concentration of $1 \times 10^{18}/\text{cm}^3$ to achieve the simulated highest solar cell efficiency of 23% (which they would not be), Hanwha and Dr. Holman have not sufficiently explained whether a POSITA would have expected the proposed modification to be successful. Hanwha asserts that a “POSITA would have had a reasonable expectation of successfully combining Choi with Granek, ... [with] only minor adjustments to the processing parameters of the dopant-diffusion process” (Pet., 39, 41), and Dr. Holman’s asserts that “only minor adjustments to the solar cell fabrication process would be required to make the solar cell of Choi with the dopant concentrations taught by Granek.” EX1003, ¶199. Contrary to Hanwha’s and Dr. Holman’s assertions, in my opinion, Granek states otherwise. Granek explains that “the solar cell

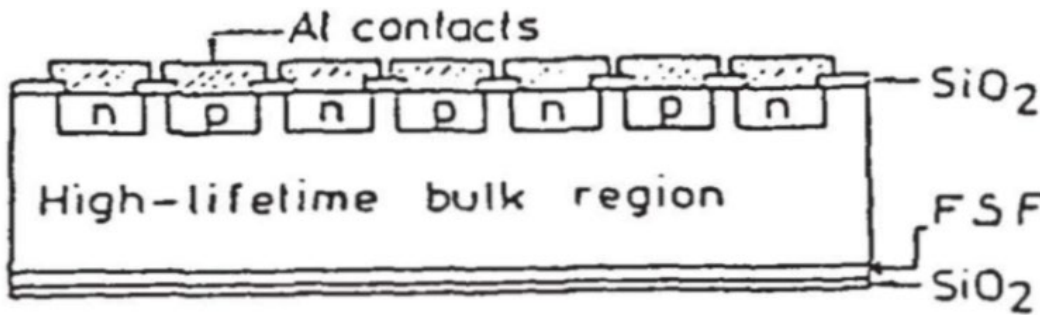
efficiencies of up to 23% could be reached by improving the solar cell optics, reduction of the overall recombination losses, minimization of the electrical shading and optimization of the cell and grid geometry, which is limited by the industrial structuring technologies.” EX1010, 176. In other words, achieving the simulated highest solar cell efficiency not only depends on optimizing the dopant concentration of the FSF layer, but also on optimizing other solar cell parameters (e.g., improving solar cell optics, reduction of recombination losses, and minimization of electrical shading). Thus, in my opinion, as Hanwha and Dr. Holman do not consider optimizing these important solar cell parameters along with the FSF dopant concentration for achieving the simulated highest solar cell efficiency, Hanwha and Dr. Holman do not show that a POSITA would have expected to successfully achieve the simulated highest solar cell efficiency if modifying Choi based on Granek’s teachings.

2. A POSITA would not have adopted Marvin’s outdated solar cell teachings—with known disadvantages—for improving Choi’s solar cell structure.

69. In my opinion, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to modify Choi with the parameters from Marvin’s outdated solar cell structure, which is known to have reliability issues.

70. Referring to Figure 1 below, Marvin discloses a solar cell with an SiO₂ layer and an FSF layer on its front surface. Marvin analyzes the efficiency of

its solar cell for different dopant concentrations of the FSF layer and different thicknesses of the solar cell. EX1008, 23. Based on this analysis, Marvin demonstrates a highest solar cell efficiency for a solar cell thickness of 50 μm and a dopant concentration of $1 \times 10^{18} \text{ cm}^{-3}$ of the FSF layer, as shown in Table 8 below. Table 8 demonstrates that increasing the thickness of Marvin's solar cell decreases the solar cell efficiency for the dopant concentration of $1 \times 10^{18} \text{ cm}^{-3}$.



EX1008, FIG. 1 (annotated).

Table 8. EOL Efficiency as a Function of cell Thickness and FSF at 100 Suns

Cell Thickness (μm)	Graded FSF (μm)	Step FSF (μm)	FSF Doping cm^{-3}	*Spacing a/b/c	Cell Efficiency (%)
50	15	—	1E18	10/20/10	14.64
50	15	—	1E18	5/10/5	15.44
65	15	—	1E18	5/10/5	11.57
80	15	—	1E18	5/10/5	8.97
200	15	—	5E18	5/10/5	1.18
65	—	0.5	5E18	5/10/5	8.17
80	—	0.5	5E18	5/10/5	6.83

Increasing
thickness

Decreasing
efficiency

EX1008, Table 8 (annotated).

71. In my opinion, both Hanwha and Dr. Holman ignore this correlation between Marvin's solar cell thickness and solar cell efficiency, when Hanwha asserts that a:

POSITA would have recognized that the dopant concentrations taught by ... Marvin would have equal application to Choi and would have been motivated to use those concentrations to reduce recombination, thereby improving efficiency. ... Further, a POSITA would have known that fabricating Choi's cell with ... Marvin's dopant concentrations would have involved a minor adjustment to one fabrication step. ... [O]nly minor adjustments to the processing parameters of the dopant-diffusion process (such as heating time and temperature) would be required. No other steps would be affected, and no additional steps would be needed.

and when Dr. Holman asserts that:

it is my opinion that only minor adjustments to the solar cell fabrication process would be required to make the solar cell of Choi with the dopant concentrations taught by Granek and Marvin.... [O]nly a small adjustment would be required to dope the front surface field at these concentrations, and a person of ordinary skill in the art would have known how to adjust the dopant concentration. For example, the heating time and temperature during the dopant diffusion process would need to be changed, but no additional processing steps or adjustments would be necessary. Furthermore, no other existing processing steps would be affected.

Pet., 38, 41; EX1003, ¶199. Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to adopt only Marvin's dopant concentration of the FSF layer in an attempt to improve Choi's solar cell efficiency, while ignoring Marvin's solar cell thickness. As I explained above in this Section, Marvin demonstrates that its solar cell efficiency depends on its solar cell thickness. Neither Hanwha nor Dr. Holman addresses this dependency.

72. In my opinion, contrary to Hanwha's and Dr. Holman's assertions, a POSITA would not have been motivated to modify Choi with Marvin's dopant concentration of the FSF layer because such modification would have led to reliability issues. Based on Marvin's teachings, Choi's solar cell would also need to be modified to have a thickness of 50 μm to achieve the improvement asserted by Hanwha and Dr. Holman. But, in my opinion, it was well known that a solar cell fabricated using a "wafer with thickness below 200 μm is fragile and susceptible to cracking during screen printing and handling processes." EX2003, 72. And, as Choi can use screen printing processes in its solar cell fabrication, a POSITA would not have been motivated to modify Choi's solar cell thickness to achieve Marvin's dopant concentration of the FSF layer because Choi's solar cell would be fragile and susceptible to cracking during fabrication. EX1006, ¶72 ("The insulating layer 40 may be formed by a variety of methods such as vacuum deposition, chemical vapor deposition, spin coating, screen printing or spray

coating”); ¶75 (“The anti-reflective film 50 may be formed by a variety of methods such as vacuum deposition, chemical vapor deposition, spin coating, screen printing or spray coating.”).

73. Thus, in my opinion, a POSITA would not have been motivated to combine Choi with Marvin’s dopant concentration of the FSF layer because such modification would have caused reliability issues.

B. Ground III: Hanwha and Dr. Holman do not show why a POSITA would have been motivated to combine Cousins with Granek or Marvin.

74. In my opinion, Hanwha and Dr. Holman do not show that a POSITA would have been motivated to combine Cousins with Granek or Marvin to teach the claimed “dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$.” In particular, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to (a) apply the front surface dopant concentration teaching from Granek’s solar cell structure with a thick passivation layer to Cousins’s solar cell structure with a thinner passivation layer, (b) adopt Marvin’s two-layer passivation solar cell teachings for improving Cousins’s three-layer passivation solar cell structure, and (c) adopt the front surface dopant concentration from Marvin’s thin solar cell structure—with known disadvantages—for improving Cousins’s thicker solar cell structure.

1. **A POSITA would not have applied the front surface dopant concentration teaching from Granek's solar cell structure with a thick passivation layer to Cousins's solar cell structure with a thinner passivation layer.**

75. Hanwha argues that “[a] POSITA would have been motivated to use Granek’s ... dopant concentration in Cousins’ doped front portion.” Pet., 68. Similarly, Dr. Holman argues that “a person of ordinary skill in the art would have had ample motivation to use the dopant concentrations disclosed in Granek ... in Cousins’ front ‘N-type doped region 105.’” EX1003, ¶362. But, in my opinion, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to look to Granek’s surface passivation structure, which is structurally different from Cousins’s surface passivation structure, to determine a front surface dopant concentration in Cousins. Rather, Hanwha ignores the structural differences between Granek’s thick surface passivation structure and Cousins’s thinner surface passivation structure and wrongly asserts that “[a] POSITA would have recognized that the dopant concentrations taught by Granek ... would have equal application to [Cousins] ... and would have been motivated to use those concentrations to reduce recombination, thereby improving efficiency.” Pet., 40, 68 (citations referring to Pet. 38). Dr. Holman also ignores the structural differences between Granek’s and Cousins’s surface passivation structures and asserts that “for Cousins, a skilled artisan would have been motivated to turn to a reference such as Granek ... to identify a concentration that would minimize recombination.”

EX1003, ¶363. As I explain below in this Section, Hanwha's and Dr. Holman's assertions are solely based on a selective, incorrect reading of Granek's front surface dopant concentration to teach the claimed "dopant concentration," while ignoring the teachings of Granek's surface passivation structure as a whole. In my opinion, Hanwha and Dr. Holman ignore the teachings of references, such as Procel, with surface passivation structures that are similar to Cousins's surface passivation structure. Procel discloses using dopant concentrations on the front surface of substrates that are higher than the claimed "dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$ " to eliminate the need for a thicker passivation layer, such as Granek's passivation layer.

a. Hanwha and Dr. Holman ignore the impact of the thickness of Granek's stack system of silicon nitride/silicon oxide passivation layers in combination with Granek's front surface dopant concentration on solar cell efficiency.

76. In my opinion, Hanwha and Dr. Holman ignore the surface passivation structure differences between Cousins and Granek, when Hanwha asserts that a POSITA "would have been motivated to use ... [Cousins's] concentrations to reduce recombination, thereby improving efficiency" and it would involve "a straightforward implementation of a dopant concentration of approximately $1 \times 10^{18} \text{ cm}^{-3}$ in the doped front portion" of Cousins (Pet., 68 (citations referring to Pet. 38), 69), and when Dr. Holman asserts that "it would

have been straightforward to apply the dopant concentration from Granek ... to the front doped region of Cousins.” EX1003, ¶366. In my opinion, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to adopt only Granek’s dopant concentration of the FSF layer in attempt to improve Cousins’s solar cell efficiency, without adopting the thicknesses of Granek’s stack system of SiO₂/SiN_x passivation layers. As I explain below in this Section, Granek demonstrates that its solar cell efficiency depends on both the parameters of its FSF layer (e.g., doping profile and dopant concentrations) and the parameters of its stack system of SiO₂/SiN_x passivation layers (e.g., thickness). EX1010, 123, 129.

77. Granek discloses a solar cell with a surface passivation structure on its front side surface for front surface passivation of the front side surface of Granek’s solar cell. Referring to Figure 4-1 (reproduced and annotated below), Granek’s surface passivation structure includes a 80 nm – 110 nm thick stack system of SiO₂/SiN_x passivation layers, which has a 70 nm thick AR SiN_x layer (highlighted blue) and a 10 nm – 40 nm thick SiO₂ layer (highlighted yellow) under the SiN_x layer. EX1010, 45-46, 55-56, 119-125. The surface passivation structure further includes an FSF layer (highlighted red) under the SiO₂ layer. EX1010, 45-46, 55-56, 119-125. Granek explains that its surface passivation structure “reduce[s] the recombination rate at the [front side] silicon surface” of its solar cell. EX1010, 119. The stack system of SiO₂/SiN_x passivation layers “reduce the density of the

surface states” on the front side surface of Granek’s solar cell. EX1010, 119. And, the FSF layer is used to “passivate[] the silicon surface by a strong reduction of holes concentration at the surface.” EX1010, 45-46, 119.

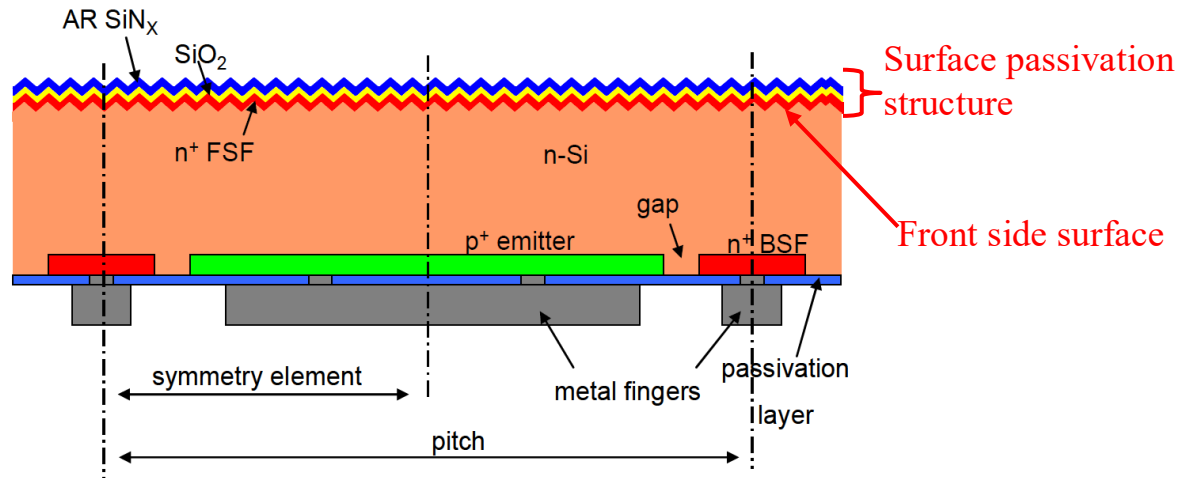


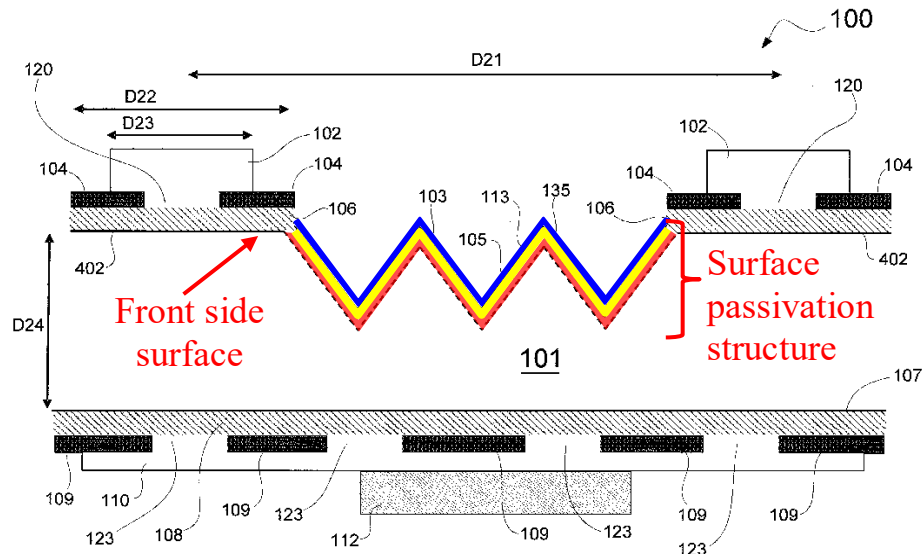
Figure 4-1 Schematic cross-section of the n-type high-efficiency back-contact back-junction silicon solar cell developed in the frame of this thesis (sketch is not to scale). Pitch and symmetry element are shown.

EX1010, FIG. 4-1 (annotated).

78. Granek analyzes “the front surface passivation quality of the phosphorus doped [FSF layer] combined with [the] stack system of SiO₂/SiN_x passivation layers” to determine the dopant concentration of the FSF layer in correlation to the stack system of SiO₂/SiN_x passivation layers for the highest solar efficiency. EX1010, 119-120. Granek concludes that “for the poorly passivated surfaces, highly doped and deep diffusion profiles are optimal in order to minimize the surface recombination [], with sheet resistance of about 10 Ω/sq. On the other hand, for the well passivated surfaces, an optimal diffusion profile is lowly doped and shallow [], with the sheet resistance of around 200 to 800 Ω/sq.” EX1010,

123. Granek further concludes that “a good surface passivation with thin SiO₂ and antireflection SiN_x layers [(e.g., 10 nm SiO₂ layer and 70 nm SiN_x layer)] have enabled processing of back-junction back-contact solar cells with efficiencies greater than 21%” EX1010, 129.

79. In contrast, Cousins discloses a solar cell 100 with a surface passivation structure thinner than Granek’s surface passivation structure. Referring to Figure 1 (reproduced and annotated below), Cousins discloses a surface passivation structure that includes a 46 nm – 70 nm thick stack of oxide/nitride passivation layers, which has a 45 nm thick silicon nitride layer 103 (highlighted blue) and a 1 nm – 25 nm thick passivating oxide 135 (highlighted yellow). EX1007, 3:3-12, 6:16-17. The surface passivation structure further includes an n-type doped region 105 (highlighted red) on its front side, which “provides low front surface recombination and improves lateral conductivity whilst not compromising the blue response of the solar cell.” EX1007, 2:49-51, 54.



EX1007, FIG. 1 (annotated).

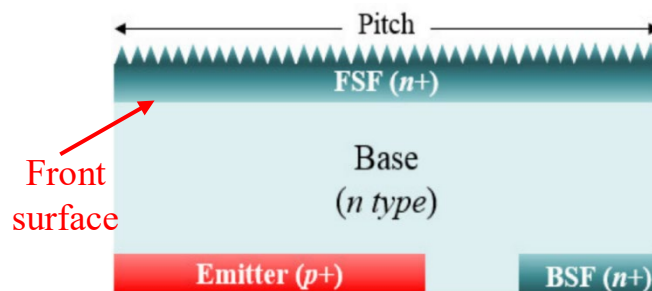
80. Thus, in my opinion, due to the structural differences between the surface passivation structures of Cousins and Granek, a POSITA would not have been motivated to modify Cousins with the teachings of Granek.

b. Hanwha and Dr. Holman do not consider solar cells with surface passivation structures similar to Cousins's solar cell.

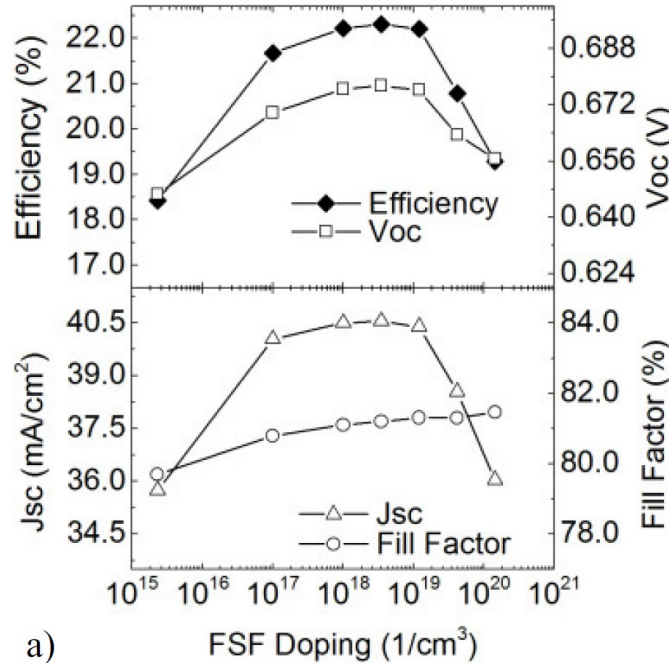
81. In my opinion, Hanwha and Dr. Holman do not show why a POSITA would have been motivated to modify Cousins with Granek despite the structural differences between them. Other references, such as Procel, with surface passivation structures similar to Cousins's report optimum dopant concentrations in their FSF layers higher than the claimed "dopant concentration of approximately less than or equal to $2 \times 10^{18} \text{ cm}^{-3}$."

82. Similar to Cousins, Procel discloses a solar cell with a relatively thinner surface passivation structure. Referring to Figure 1 (reproduced and

annotated below), Procel discloses a surface passivation structure that includes a 69 nm thick stack of $\text{SiO}_2/\text{Si}_3\text{N}_4$ passivation layers—a 42 nm thick Si_3N_4 layer (not shown in Figure 1) and a 27 nm thick SiO_2 layer (not shown in Figure 1)—and an FSF region (highlighted blue in Figure 1) on its front surface. EX2005, 129 (“1 μm for FSF region. ... The front surface is coated by double-layer Anti-Reflective Coating (ARC) composed by 42nm Si_3N_4 and 27nm SiO_2 ,... while the back side is passivated by a 0.1 μm of SiO_2 .”). Procel’s 69 nm thick stack of $\text{SiO}_2/\text{Si}_3\text{N}_4$ passivation layers is similar in thickness to Cousins’s 46 nm – 70 nm thick stack of oxide/nitride passivation layers discussed above in Section V.B.1a. Procel further discloses that “the optimum values of peak doping are: ... $3.47 \times 10^{18} \text{ cm}^{-3}$ for FSF” region. At this peak doping, Procel demonstrates in Figure 4a below that the solar cell efficiency is greater than 22%. EX2005, 132.



EX2005, FIG. 1 (annotated).



EX2005, FIG. 4a (annotated).

83. Thus, in my opinion, a POSITA would have understood that Procel demonstrates achieving high solar cell efficiency with thin passivation layers, which would require less processing time and lower manufacturing costs than that required for manufacturing Granek's solar cells with thicker passivation layers. Accordingly, a POSITA would not have been motivated to modify Cousins's n-type doped region 105 with Granek's FSF dopant concentration of $1 \times 10^{18} \text{ cm}^{-3}$, as asserted by Hanwha and Dr. Holman. Pet., 69; EX1003, ¶367.

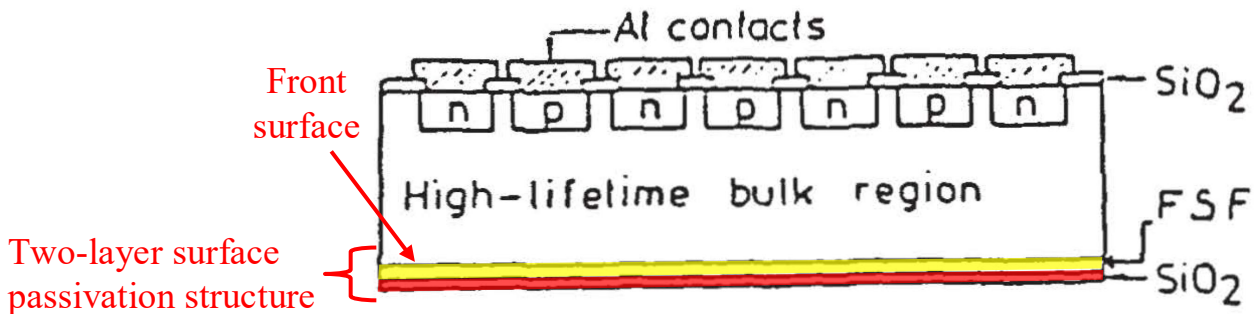
2. A POSITA would not have adopted Marvin's two-layer passivation solar cell teachings for improving Cousins's three-layer passivation solar cell structure.

84. Hanwha argues that "[a] POSITA would have been motivated to use Marvin's ... dopant concentration in Cousins's doped front portion." Pet., 68.

Similarly, Dr. Holman argues that “a person of ordinary skill in the art would have had ample motivation to use the dopant concentrations disclosed in ... Marvin in Cousins’ front ‘N-type doped region 105.’” EX1003, ¶362. But, in my opinion, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to look to Marvin’s two-layer surface passivation structure, which is structurally different from Cousins’s three-layer surface passivation structure, to determine a front surface dopant concentration in Cousins. Rather, Hanwha ignores these structural differences and wrongly asserts that “[a] POSITA ... would have been motivated to use [Marvin’s FSF dopant] concentrations to reduce recombination, thereby improving efficiency.” Pet., 68 (citations referring to Pet. 38). Dr. Holman also ignores the structural differences between Granek’s and Cousins’s surface passivation structures and asserts that “for Cousins, a skilled artisan would have been motivated to turn to a reference such as ... Marvin to identify a concentration that would minimize recombination.” EX1003, ¶363. As I explain below in this Section, Hanwha and Dr. Holman do not show why a POSITA would have been motivated to adopt Marvin’s FSF dopant concentration for improving solar cell efficiency despite these structural differences. In my opinion, Hanwha and Dr. Holman ignore the teachings of references with similar surface passivation structures as Cousins’s solar cell, such as Procel’s solar cell,

that disclose higher dopant concentrations and higher solar cell efficiencies than Marvin's solar cell.

85. Referring to Figure 1 (reproduced and annotated below), Marvin discloses a solar cell with a two-layer surface passivation structure having an SiO₂ layer (highlighted yellow) and an FSF layer (highlighted red) on its front surface. Marvin analyzes the solar cell efficiency of its solar cell for different dopant concentrations of the FSF layer and different thicknesses of the solar cell. EX1008, 23. Based on this analysis, Marvin demonstrates a highest solar cell efficiency of 15.44% for a solar cell thickness of 50 μm and a dopant concentration of 1×10^{18} cm⁻³ of the FSF layer, as shown in Table 8 below.



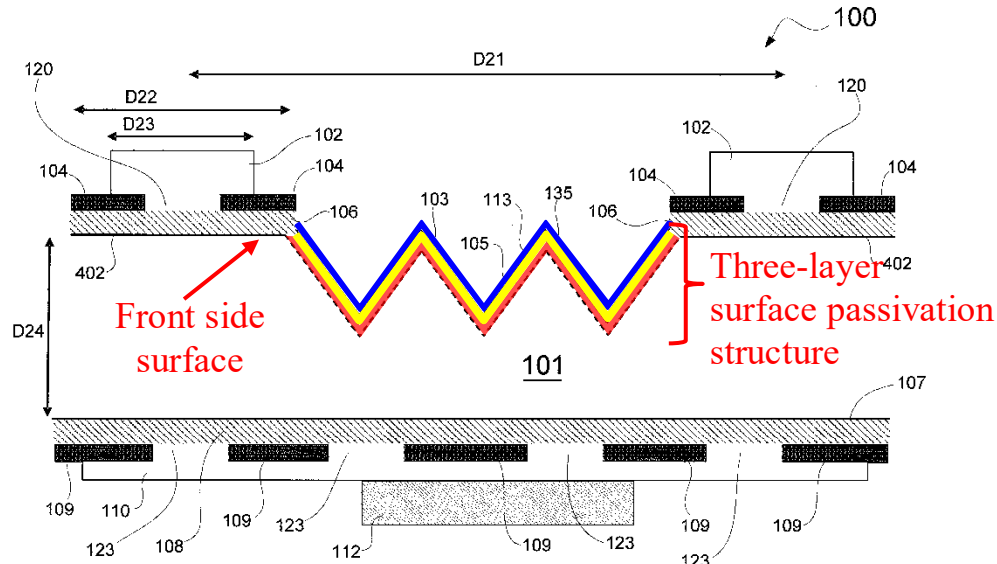
EX1008, FIG. 1 (annotated).

Table 8. EOL Efficiency as a Function of cell Thickness and FSF at 100 Suns

Cell Thickness (μm)	Graded FSF (μm)	Step FSF (μm)	FSF Doping cm ⁻³	*Spacing a/b/c	Cell Efficiency (%)
50	15	—	1E18	10/20/10	14.64
50	15	—	1E18	5/10/5	15.44
65	15	—	1E18	5/10/5	11.57
80	15	—	1E18	5/10/5	8.97
200	15	—	5E18	5/10/5	1.18
65	—	0.5	5E18	5/10/5	8.17
80	—	0.5	5E18	5/10/5	6.83

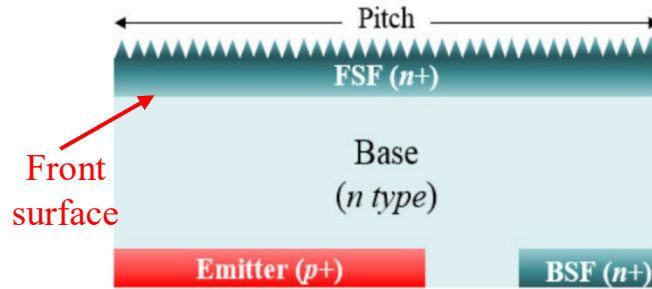
EX1008, Table 8 (annotated).

86. In contrast, Cousins discloses a solar cell 100 with a three-layer surface passivation structure. Referring to Figure 1 (reproduced and annotated below), Cousins's three-layer surface passivation structure includes a silicon nitride layer 103 (highlighted blue), a passivating oxide 135 (highlighted yellow), and an n-type doped region 105 (highlighted red) on its front surface. EX1007, 2:49-51, 3:3-12, 6:16-17. The n-type doped region 105 "provides low front surface recombination and improves lateral conductivity whilst not compromising the blue response of the solar cell." EX1007, 2:51-54.

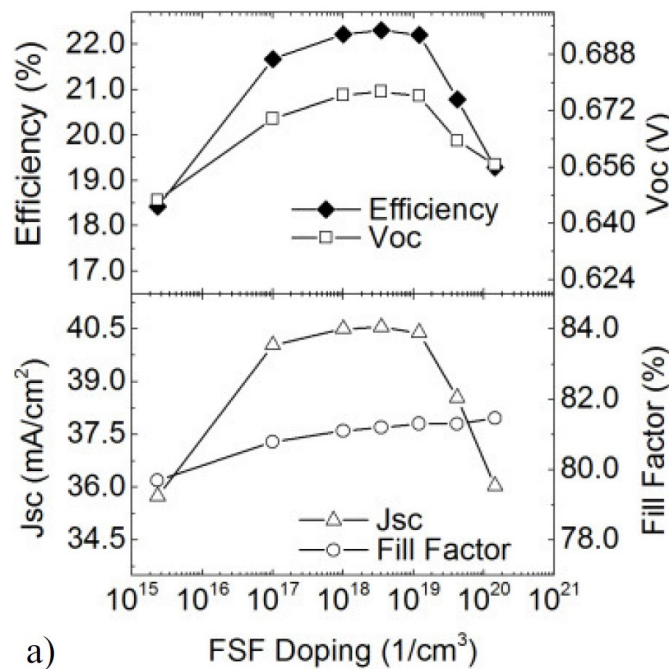


EX1007, FIG. 1 (annotated).

87. Similar to Cousins, Procel discloses a solar cell with a three-layer surface passivation structure. Referring to Figure 1 (reproduced and annotated below), Procel's three-layer surface passivation structure includes an Si_3N_4 layer (not shown in Figure 1), an SiO_2 layer (not shown in Figure 1), and an FSF region (highlighted blue in Figure 1) on its front surface. EX2005, 129 ("1 μm for FSF region. ... The front surface is coated by double-layer Anti-Reflective Coating (ARC) composed by 42nm Si_3N_4 and 27nm SiO_2 ,... while the back side is passivated by a 0.1 μm of SiO_2 ."). Procel further discloses that "the optimum values of peak doping are: ... $3.47 \times 10^{18} \text{ cm}^{-3}$ for FSF" region. At this peak doping, Procel demonstrates in Figure 4a (below) that the solar cell efficiency is greater than 22%, which is greater than Marvin's highest solar cell efficiency of 15.44% (discussed above in this Section). EX2005, 132.



EX2005, FIG. 1 (annotated).



EX1007, FIG. 4a.

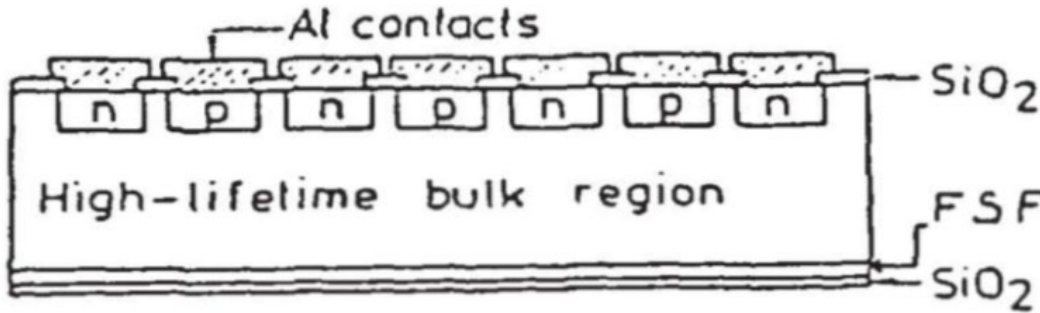
88. In my opinion, in view of the above structural differences between the surface passivation structures of Cousins and Marvin, a POSITA would not have been motivated to modify Cousins based on Marvin. This is because Marvin discloses a much lower solar cell efficiency (of 15.44%) than solar cells with similar surface passivation structures as Cousins, such as Procel's solar cell (having an efficiency greater than 22%). Thus, in my opinion, a POSITA would

have not been motivated to combine Cousins with Marvin to teach or suggest the claimed “dopant concentration of approximately less than or equal to 2×10^{18} cm^{-3} .”

3. A POSITA would not have adopted the front surface dopant concentration from Marvin’s thin solar cell structure—with known disadvantages—for improving Cousins’s thicker solar cell structure.

89. In my opinion, Hanwha does not show why a POSITA would have been motivated to modify Cousins with the design parameters from Marvin’s outdated solar cell structure, which is known to have reliability issues.

90. Referring to Figure 1 below, Marvin discloses a solar cell with an SiO_2 layer and an FSF layer on its front surface. Marvin analyzes the solar cell efficiency of its solar cell for different dopant concentrations of the FSF layer and different thicknesses of the solar cell. EX1008, 23. Based on this analysis, Marvin demonstrates a highest solar cell efficiency for a solar cell thickness of $50 \mu\text{m}$ and a dopant concentration of $1 \times 10^{18} \text{ cm}^{-3}$ of the FSF layer, as shown in Table 8 below. Table 8 demonstrates that increasing the thickness of Marvin’s solar cell decreases the solar cell efficiency for the dopant concentration of $1 \times 10^{18} \text{ cm}^{-3}$.



EX1008, FIG. 1.

Table 8. EOL Efficiency as a Function of cell Thickness and FSF at 100 Suns

Cell Thickness (μm)	Graded FSF (μm)	Step FSF (μm)	FSF Doping cm ⁻³	*Spacing a/b/c	Cell Efficiency (%)
50	15	—	1E18	10/20/10	14.64
50	15	—	1E18	5/10/5	15.44
65	15	—	1E18	5/10/5	11.57
80	15	—	1E18	5/10/5	8.97
200	15	—	5E18	5/10/5	1.18
65	—	0.5	5E18	5/10/5	8.17
80	—	0.5	5E18	5/10/5	6.83

Increasing
thickness

Decreasing
efficiency

EX1008, Table 8 (annotated).

91. In my opinion, both Hanwha and Dr. Holman ignore this correlation between Marvin’s solar cell thickness and its solar cell efficiency when Hanwha asserts that a POSITA “would have been motivated to use ... [Marvin’s] concentrations to reduce recombination, thereby improving efficiency” and it would involve “a straightforward implementation of a dopant concentration of approximately $1 \times 10^{18} \text{ cm}^{-3}$ in the doped front portion” of Cousins (Pet., 68 (citations referring to Pet. 38), 69), and when Dr. Holman asserts that “it would have been straightforward to apply the dopant concentration from ... Marvin to the

front doped region of Cousins.” EX1003, ¶366. Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to adopt only Marvin’s dopant concentration of the FSF layer to improve Cousins’s solar cell efficiency while ignoring Marvin’s solar cell thickness. As I explained above in this Section, Marvin demonstrates that its solar cell efficiency depends on its solar cell thickness. Neither Hanwha nor Dr. Holman addresses this dependency.

92. In my opinion, contrary to Hanwha’s and Dr. Holman’s assertions, a POSITA would not have been motivated to modify Cousins with Marvin’s dopant concentration of the FSF layer because such modification would have led to reliability issues. Based on Marvin’s teachings, Cousins’s solar cell would also need to be modified to have a thickness of 50 μm to achieve the improvement asserted by Hanwha and Dr. Holman. But, in my opinion, it was well known that a solar cell fabricated using a “wafer with thickness below 200 μm is fragile and susceptible to cracking during screen printing and handling processes.” EX2003, 72. And, as Cousins uses screen printing processes for its solar cell fabrication, a POSITA would not have been motivated to modify Cousins’s solar cell thickness to achieve Marvin’s dopant concentration of the FSF layer because Cousins’s solar cell would be fragile and susceptible to cracking during fabrication. EX1007, 6:40-42 (“The metal contact 110 may be formed using a printing process, such as screen printing.”).

93. Thus, in my opinion, a POSITA would not have been motivated to combine Cousins with Marvin's dopant concentration of the FSF layer because such modification would have caused reliability issues.

VI. ALL GROUNDS: HANWHA AND DR. HOLMAN DO NOT SHOW THAT THE PRIOR ART COMBINATIONS TEACH OR SUGGEST THE CLAIMED "FIRST EMITTER REGION HAVING METAL IMPURITIES" AND "SECOND EMITTER REGION HAVING METAL IMPURITIES."

94. Both Hanwha and Dr. Holman rely on Istratov (EX1012) to teach the claimed "first emitter region having metal impurities" and "second emitter region having metal impurities." In my opinion, Hanwha and Dr. Holman rely on hindsight for the proposed combination of Choi and Istratov and do not consider how the proposed combination would change Choi's solar cell operation. Similarly, in my opinion, Hanwha and Dr. Holman rely on hindsight for the proposed combination of Cousins and Istratov and do not consider how the proposed combination would degrade Cousins's solar cell performance.

A. Grounds I and II: Hanwha and Dr. Holman do not show why a POSITA would have been motivated to combine Choi with Istratov.

95. In my opinion, Hanwha and Dr. Holman do not show how a POSITA would have been motivated to modify Choi with Istratov without hindsight or without changing Choi's solar cell operation for at least the following three reasons.

96. *First*, Hanwha and Dr. Holman do not explain which of Istratov's gettering processes would be used in Choi's solar cell fabrication process. Hanwha acknowledges Istratov's different processes for gettering different impurities and states that "[f]or iron, Istratov teaches that heating for "8 h[ours]" "at 1020°C" was "sufficient to equilibrate the iron through the SiO₂ layer" and "[f]or copper, Istratov teaches that heating "at 690 °C for 5 h[ours]" and "at 1150 °C for 2h[ours]" resulted in copper diffusion from the silicon substrate to the polysilicon layer." Pet., 46. And, Hanwha argues that "Choi teaches a thermal-treatment step during doping of the first and second conductive type areas" and that "[a] POSITA would have recognized that this step would have been used to getter metals from the substrate to the first and second conductive type areas, through heating the cell to a sufficiently high temperature." Pet., 45-46. But, in my opinion, Hanwha does not explain which of Istratov's gettering processes and process conditions would be used "during doping of the first and second conductive type areas" in Choi. Pet., 46. Instead, Hanwha broadly states that "a POSITA would have used Istratov's instructions or merely selected a higher temperature and heated the cell for enough time to induce gettering." Pet., 46.

97. Also, in my opinion, Dr. Holman provides no clarification and broadly comments that:

A person of ordinary skill in the art would have known that [Choi's] thermal treatment step would have been used to getter metals from the substrate to the first and second conductive type areas by simply heating the solar cell to a high enough temperature. To the extent that an existing processing temperature was not high enough or an existing heating time was not long enough, a person of ordinary skill in the art would merely have had to increase the temperature of the tube furnace that the solar cell was heated in or the heating time to cause gettering.

EX1003, ¶211. Thus, in my opinion, it is unclear from Hanwha's and Dr.

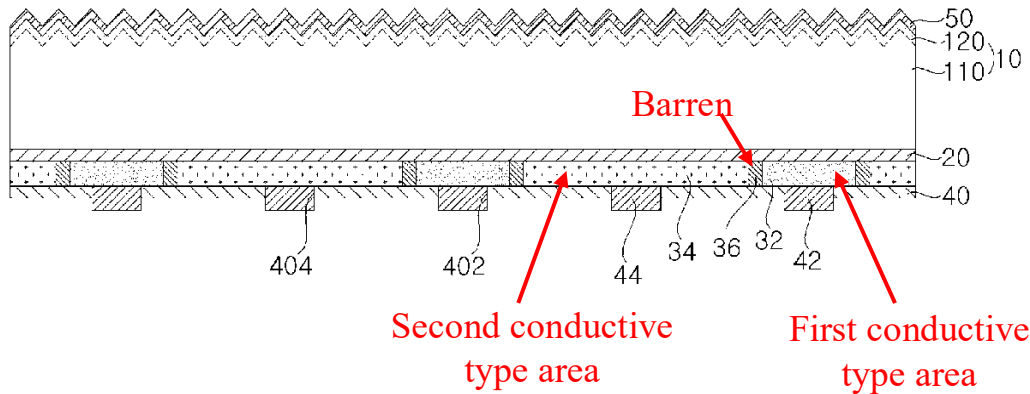
Holman's arguments for the proposed combination of Choi and Istratov which of Istratov's gettering processes (or both) that Hanwha proposes to implement in Choi to teach the claimed "first emitter region having metal impurities" and "second emitter region having metal impurities."

98. *Second*, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to look to Istratov's gettering processes for iron and copper impurities in a silicon substrate, despite Choi's lack of disclosure of any metal impurities in its monocrystalline silicon substrate. In my opinion, as Istratov discloses different process conditions for gettering iron and copper impurities from the silicon substrate to a polysilicon layer, without the benefit of hindsight, a POSITA would not have been motivated to implement Istratov's gettering process conditions in Choi without having knowledge of the type of impurities, if any, present in Choi's monocrystalline silicon substrate.

99. *Third*, Hanwha and Dr. Holman do not explain how Istratov's high-temperature gettering processes could be used in Choi without changing Choi's solar cell operation. In particular, Hanwha and Dr. Holman do not explain how using Istratov's high-temperature gettering process conditions during doping of Choi's first and second conductive type areas 32 and 34, as proposed by Hanwha and Dr. Holman, would prevent an undesirable short between Choi's first and second conductive type areas 32 and 34.

100. Referring to Figure 1 (reproduced and annotated below), Choi discloses a solar cell 100 with a barren area 36, which is "an undoped insulating material (for example, oxide or nitride) or the like" or "amorphous silicon, microcrystalline silicon or polycrystalline silicon," and is "interposed between the first conductive type area 32 and the second conductive type area 34." EX1006, ¶¶38-39. The first conductive type area 32 "may be easily formed by doping amorphous silicon, microcrystalline silicon, polycrystalline silicon or the like with a first conductive type dopant" and the second conductive type area 34 "may be easily formed by doping amorphous silicon, microcrystalline silicon, polycrystalline silicon or the like with a second conductive type dopant...." EX1006, ¶¶36-37. Choi further discloses that "[a]s a result [of the barren area 36], shunt caused by undesired short between the first conductive type area 32 and the second conductive type area 34 can be prevented." EX1006, ¶56.

101. In my opinion, from this disclosure, a POSITA would have understood that, for Choi's solar cell to function properly, the barren area 36 needs to remain undoped and electrically non-conductive between the first conductive type area 32 and the second conductive type area 34 to prevent an undesirable short between the two conductive areas. However, a POSITA would have understood that implementing Istratov's high-temperature gettering process (e.g., gettering process for iron at 1020 °C, gettering process for copper at 690 °C and at 1150 °C, discussed above in this Section) during doping of Choi's first and second conductive type areas 32 and 34 would diffuse dopants from the first and second conductive type areas 32 and 34 into the undoped barrier area 36. This is because the first and second conductive type areas 32 and 34 have higher dopant concentrations than the undoped barren area 36, and it is well known that "during the high thermal annealing process [at a temperature over 800 °C,] ... dopants tend to diffuse from a region of higher concentration, such as the poly-Si layer, to that of lower concentration, such as the c-Si absorber." EX2004, 5. Thus, in my opinion, such dopant diffusion into the barren area 36 would cause an undesirable short between the first conductive type area 32 and the second conductive type area. In my opinion, this undesirable short compromises the insulating function of the barren area 36, thus changing the operation of Choi's solar cell 100.



EX1006, FIG. 1 (annotated).

102. Thus, for at least the above reasons and in my opinion, Hanwha does not show why a POSITA would have been motivated to modify Choi based on Istratov's teachings.

B. Ground III: Hanwha and Dr. Holman do not show why a POSITA would have been motivated to combine Cousins with Istratov.

103. In my opinion, Hanwha and Dr. Holman do not show how a POSITA would have been motivated to modify Cousins with Istratov without hindsight or degrading Cousins's solar cell performance for at least the following three reasons.

104. *First*, Hanwha and Dr. Holman do not explain which of Istratov's gettering processes would be used in Cousins and how these gettering processes would be implemented in Cousins's solar cell fabrication process. Hanwha only states that "a POSITA would have been motivated to add Istratov's gettering process" in Cousins because the "back area of the cell in Cousins is readily modifiable using Istratov's gettering into the polysilicon region. ... Cousins' cell

structure (like Choi's) includes a substrate and an emitter region ("polysilicon layer 108") into which metal impurities from the substrate would be gettered using the Istratov process to getter impurities into a polysilicon layer of the solar cell." Pet., 70-71. But, in my opinion, Hanwha does not explain which of Istratov's gettering processes and process conditions would be used to modify the "back area of the cell in Cousins." Pet., 71. Also, in my opinion, Dr. Holman provides similar broad statements with no explanation or clarification. EX1003, ¶¶371, 373. Thus, in my opinion, it is unclear from Hanwha's and Dr. Holman's arguments for the proposed combination of Cousins and Istratov which of Istratov's gettering processes (or both) is being implemented in Cousins to teach the claimed "first emitter region having metal impurities."

105. *Second*, Hanwha and Dr. Holman do not show why a POSITA would have been motivated to look to Istratov's gettering processes for iron and copper impurities in a silicon substrate, despite Cousins's lack of disclosure of any metal impurities in its silicon substrate. In my opinion, as Istratov discloses different process conditions for gettering iron and copper impurities from the silicon substrate to a polysilicon layer, without the benefit of hindsight, a POSITA would not have been motivated to implement Istratov's gettering process conditions in Cousins without having knowledge of the type of impurities, if any, present in Cousins's silicon substrate.

106. *Third*, Hanwha and Dr. Holman do not show how Istratov's high-temperature gettering processes could be used in Cousins without degrading solar cell performance. In particular, Hanwha and Dr. Holman do not explain how using Istratov's high-temperature gettering process conditions would not adversely affect contact resistance between Cousins's metal contacts 102 and substrate 101.

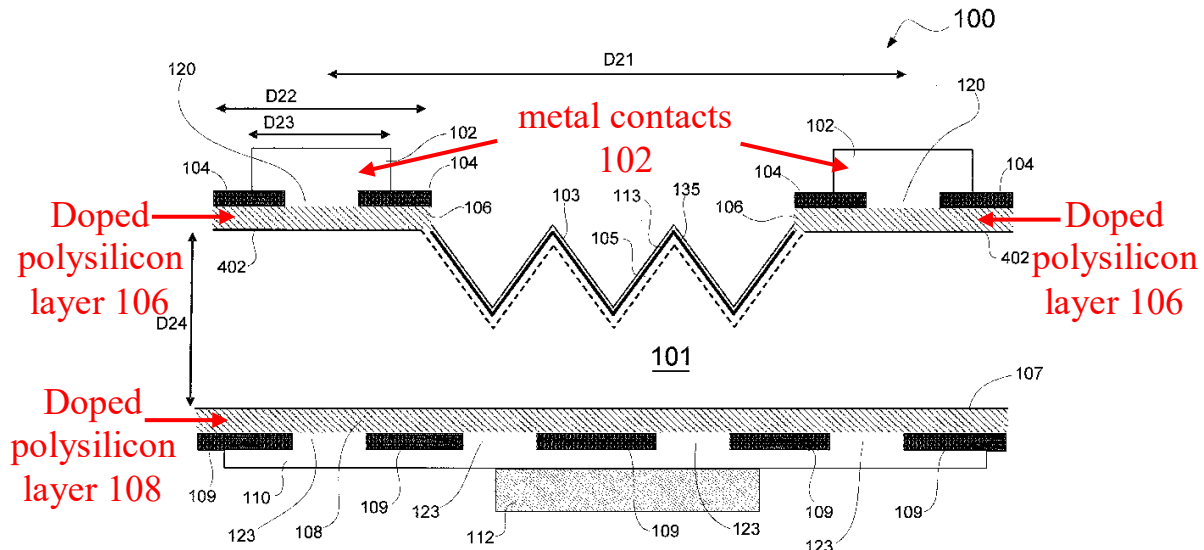
107. Referring to Figure 1 (reproduced and annotated below), Cousins discloses a solar cell 100 with "a front side where metal contacts 102 are located.... [E]ach metal contact 102 electrically connects to the [doped] polysilicon layer 106 through a contact hole 120 formed through the silicon dioxide layer 104." EX1007, 2:31-32, 3:47-50. Cousins further discloses that "the metal contacts 102 are formed on the silicon dioxide layer 104 to fill the contact holes 120 and make electrical connection to the substrate 101 by way of the [doped] polysilicon layer 106[, which] ... provides low contact resistance and minimizes contact recombination" between the metal contacts 102 and the substrate 101. EX1007, 2:56-58, 6:51-54. Cousins also discloses that "[t]he polysilicon layer 106 may be formed on a thin dielectric layer 402. The thin dielectric layer 402 may comprise silicon dioxide thermally grown to a thickness of about 10 to 50 Angstroms on the front side surface of the substrate 101." EX1007, 2:64-67.

108. In my opinion, from this disclosure, a POSITA would have understood that front-side passivating contacts with the doped polysilicon layer

106 and thin silicon dioxide layer 402 between the metal contacts 102 and the silicon substrate 101 are formed in Cousins to minimize recombination losses and contact resistance at the metal contacts 102. It was well known that recombination losses at metal contacts are reduced in such passivating contacts by preventing a direct contact between the metal contacts and the substrate. EX2004, 1-2 (“Passivating contacts using polycrystalline silicon (poly-Si) formed on the thin silicon oxide (SiO_x) surface of c-Si, referred to briefly as poly Si/c-Si contacts, represent a state-of-the-art passivating technology for c-Si solar cells. This technology considerably restricts the recombination losses due to the direct contact between the c-Si/metal...”)

It was also known that exposing the doped polysilicon layer in passivating contacts to high temperatures over 800 °C causes dopants to diffuse out of the doped polysilicon layer and into the substrate, which increases recombination losses and degrades the passivating quality of the passivating contacts. EX2004, 2 (“During the annealing process [at a temperature over 800 °C], dopants from poly-Si layers can diffuse extensively into the c-Si absorber and compromise the passivation quality.”) Thus, in my opinion, a POSITA would have understood that implementing Istratov’s high-temperature gettering process (e.g., gettering process for iron at 1020 °C, gettering process for copper at 690 °C and at 1150 °C, discussed above in Section VI.A) in Cousins would cause dopants to diffuse out of Cousins’s doped polysilicon layer 106 and into the substrate 101

and undesirably increase recombination losses at the metal contacts 102, thus degrading Cousins's solar cell performance.



109. Thus, for at least the above reasons and in my opinion, Hanwha does not show why a POSITA would have been motivated to modify Cousins based on Istratov's teachings.

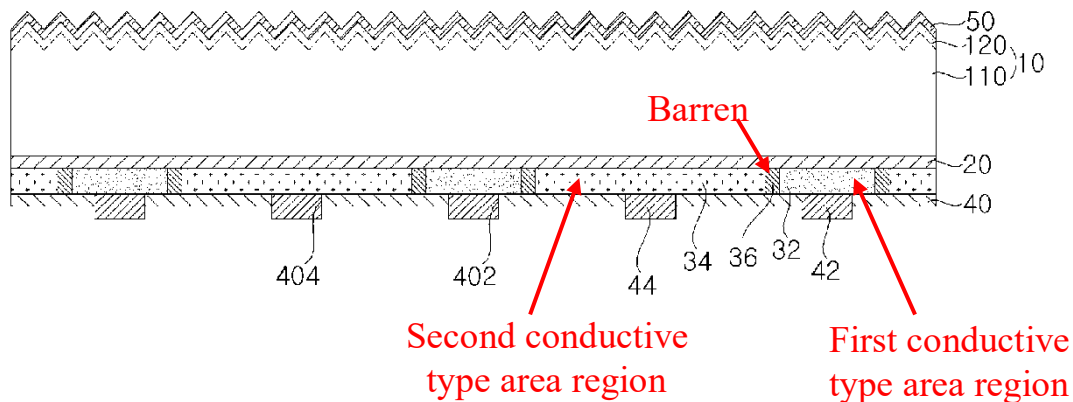
VII. GROUND II: HANWHA AND DR. HOLMAN DO NOT SHOW WHY A POSITA WOULD HAVE BEEN MOTIVATED TO MODIFY CHOI'S SOLAR CELL TO INCORPORATE THE CLAIMED "TRENCH REGION"—DESPITE CHOI'S TEACHINGS AGAINST SUCH MODIFICATION.

110. In my opinion, Hanwha and Dr. Holman do not show why a POSITA would have been motivated to modify Choi with Smith's trench. Hanwha argues that "[a] POSITA would have found it obvious to use a trench, as taught by Smith, to isolate the P-type and N-type emitter regions" in Choi. Pet., 63. To support this argument, Hanwha states that "[a] POSITA would have been motivated to

implement [in Choi's solar cell]... a trench as taught by Smith to improve efficiency [because] ... directly abutting p-type and n-type doped regions adversely affect efficiency." Pet., 63. Dr. Holman provides similar argument: "a person of ordinary skill in the art would have had ample motivation to use such a trench to separate the n-type and p-type emitter regions in the Choi solar cell..." But, in my opinion, none of Hanwha's and Dr. Holman's arguments explain why a POSITA would have been motivated to modify Choi with Smith's trench for at least the following three reasons.

111. *First*, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to implement Smith's trench in Choi, despite Choi's solar cell already having a barren area 36 that performs the same function for achieving the same benefits as Smith's trench. In particular, referring to Figure 1 (reproduced and annotated below), Choi discloses a solar cell 100 including "a first conductive type area 32 having a first conductive type dopant [(e.g., p-type)], a second conductive type area 34 having a second conductive type dopant [(e.g., n-type)], and a barrier area 36 formed between the first conductive type area 32 and the second conductive type area 34 are formed on the tunneling layer 20.... [T]he barren area 36 may include a variety of materials for substantially insulating the first conductive type area 32 from the second conductive type area 34 ... [and] surrounds the first conductive type area 32 to separate the first conductive type

area 32 from the second conductive type area 34 and thereby prevents generation of undesired shunt.” EX1006, ¶¶26, 35, 39, 51. In other words, Choi’s barren area 36 electrically isolates Choi’s p-type doped region 32 from n-type doped region 34, thus performing the same function as Smith’s trench. In my opinion, Hanwha and Dr. Holman do not acknowledge the teachings of Choi’s barren area 36, much less why a POSITA would have been motivated to modify Choi with another structure like Smith’s trench that serves the same function as the barren area 36.



EX1006, FIG. 1 (annotated).

112. *Second*, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to modify Choi with Smith’s trench, despite Choi discouraging from such modification. In particular, Choi discloses that “[u]nlike the present embodiment [with the barren area 36], when the first and second conductive type areas [32 and 34] are separated by etching portions [(e.g., forming a trench)] between the first and second conductive type areas, a portion of the semiconductor substrate is etched and is thus exposed to the outside. As a result,

the semiconductor substrate is damaged and properties of solar cell are deteriorated. In order to prevent these problems, an additional passivation layer should be formed in a portion of the semiconductor substrate exposed to the outside. As a result, qualities and production efficiency of solar cells are deteriorated.” EX1006, ¶79. In other words, rather than form a trench to separate the first and second conductive type areas, Choi discloses forming an additional passivation layer in the substrate to prevent solar cell damage and deterioration. In my opinion, Hanwha and Dr. Holman do not address this explicit teaching that would have discouraged a POSITA from forming a trench in Choi’s solar cell structure.

113. *Third*, Hanwha and Dr. Holman do not explain why a POSITA would have been motivated to modify Choi with Smith’s trench, when such modification would add additional steps to Choi’s solar cell fabrication process. In my opinion, increasing the complexity of Choi’s manufacturing method by increasing the number of steps in Choi’s solar cell fabrication process directly contradicts Choi’s express objective of “simplifying manufacturing method of the solar cell 100 and improving production efficiency.” EX1006, ¶78.

114. Thus, for at least the above reasons and in my opinion, Hanwha and Dr. Holman do not show why a POSITA would have been motivated to modify Choi in view of Smith’s teachings.

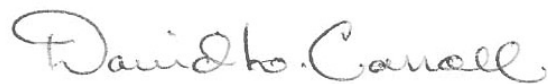
VIII. CONCLUSION

115. I understand that this Declaration is to be filed as evidence in a contested IPR proceeding before the Patent Trial and Appeal Board. I acknowledge that I may be subject to cross-examination in the case and that cross-examination will take place within the United States. If cross-examination is required of me, I will appear for cross-examination within the United States during the time allotted for cross-examination.

116. I hereby declare under penalty of perjury that the foregoing is true and correct, that all statements made herein of my own knowledge are true, and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like are punishable by fine or imprisonment, or both, under 18 U.S.C. § 1001 and may jeopardize the validity of the application or any patent issuing thereon. If called to testify as to the truth of the matters stated herein, I could and would testify competently.

Respectfully submitted,

Dated: November 26, 2024



David L. Carroll, Ph.D.

Appendix A

Curriculum Vitae

Wake vs. Duke 21 - 0
 NCSU vs. UNC 14 - 7
 VaTech vs. ECU 10 - 3
 App vs. Furman 24 - 10

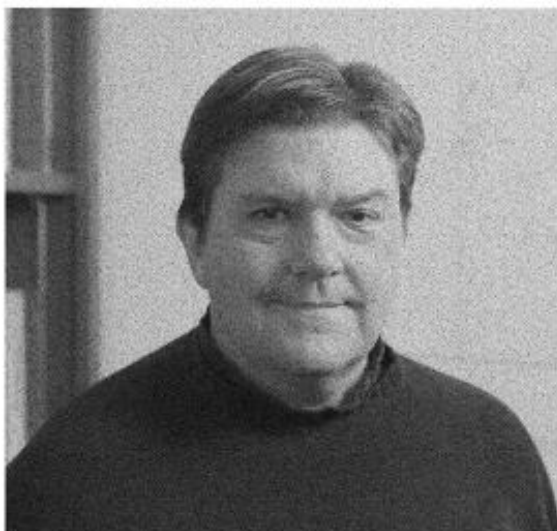
WINSTON - SALEM JOURNAL

Weather: showers in the am becoming clear by early afternoon. Temps. in the low 70s

Issue number 93

Winston Salem NC Monday October 24, 2023

Newstand price 50 cents



The Rules of Physics Have Changed

Winston-Salem (NC) - Wake Forest University's famed Nanotechnology Center announced at the recent Materials Research Society Meeting in Honolulu, that it had successfully created an operational Qubit at room temperature using topologically complex materials. "This was thought practically to be impossible" said leader of the research team Dr. David Carroll, "but I guess nature had other plans.." (cont'd)



NANOTECH and The Energy Crisis

Winston-Salem (NC) - Prof Carroll and his NANOTECH team are to be featured in the MRS Bulletin recognizing their pioneering work in the creation of the HyStirE solar panel. HyStirE (pronounced like *history*), which stands for Hybrid Stirling Engine combines thermal energy capture in fluids with photovoltaics made from silicon, to nearly double the energy collection of a standard rooftop solar array. The technology was recognized in a recent Materials Research Society Symposium on solar energy. "Surprisingly, these panels can withstand high winds and shear like you would see in hurricanes, making them ideal for the east coast" said Prof Carroll. (cont'd)

NANOTECH Has Gone Hollywood

Winston-Salem (NC) - In another development, Powerfelt™ a material developed by WFU's Nanotechnology Center and reported by CNN as well as the NYT, has been featured in the 2020 movie *Interpreters*. This Sci Fi thriller features Rachel Kylian, Terry Maratos and Ace Marrero and was written and directed by Michael Ryan for Archetype Pictures. "Apparently it helps the bad guys take over the world" according to Prof Carroll head of the Powerfelt™ development team. Carroll only recently watched the movie.

Who is This Prof. Carroll?

Winston-Salem (NC) - Prof. Carroll of Wake Forest University's renown Center for Nanotechnology and Molecular Materials (NANOTECH) recently interviewed by

The Curriculum Vitae of
Dr. David Carroll



David L. Carroll PhD.

Fellow of the American Physical Society
Professor of Physics
Director, Center for Nanotechnology and Molecular Materials

Wake Forest University
Winston-Salem NC 27109
Email: carrolldl@wfu.edu

Personal Information

DOB: 13/01/1963

Family Status: married - one child (WFU '22)

Personal Statement

In a broad sense, my research focuses on the fundamental aspects of dimensionality, symmetry breaking and topology in a range of materials systems. The work emphasizes discovery of anomalous emergent electrical, magnetic, optical, and thermodynamic properties in low-dimensional materials as symmetry breaking is introduced or topologies become complex. Systems of interest include: synthetic metals such as polymers, carbon nanotubes, and graphene as well 2D inorganic systems such as chalcogenide compounds. While recent work has focused on systems that encode quantum information, it is by nature applicable to a broad variety of technologies including thermoelectrics, solar collection and lighting systems, as well as biosensors and bioelectronics. Both the fundamental and applied aspects of the work are embraced.

- **Nanomaterials/Quantum Materials:** Studies in transport, optical, magnetic, and thermal properties of nano-scale systems, quantum information systems, emergent quantum behavior. Fundamental mechanisms for quantum information flow.
- **Organic device technologies:** OLEDs, Thin Film Electroluminescent Devices, Organic Photovoltaics (OPVs), Organic Light Emitting Transistors, Nanocomposite Electrochromics and organic thermoelectric/piezoelectric power generation.
- **Biomedical nanosciences:** Biomedical applications of nanomaterials, biosensors and bioelectronics, tissue scaffolding and regeneration, photo-thermal therapeutics for cancer treatment.
- **Materials Characterization:** Scanning probe microscopy/spectroscopy STM, AFM, MFM, STS high resolution electron microscopy/spectroscopy HRTEM, STEM, SEM, EDS, PEELS, Component analysis XPS, Auger.

Contents

- Section 1** Educational and Professional Experience
- Section 2** Awards and Honors
- Section 3** Products of Scholarship
Publications, Patents, Sponsored Programs, Presentations
- Section 4** Teaching and Mentoring
Courses, Techniques, Quality Assessments, Mentoring Students
- Section 5** Service
Professional and University Service, the Nanotech Center, Community Outreach

1. EDUCATIONAL and PROFESSIONAL EXPERIENCE



1.1 Advisors

Dr. Dale Doering - Wesleyan University, PhD. thesis Advisor.

Dr. Dawn Bonnell - University of Pennsylvania, Postdoctoral Advisor.

Prof. Manfred Rühle - Max-Planck-Institut für Metallforschung, Postdoctoral Advisor.

Dr. Siegmur Roth - Max-Planck-Institut für Festkörperforschung, Career Advisor.

1.2 Degrees Conferred

Ph.D. Wesleyan University, Middletown CT, Physics, 1993
 Dissertation: *Defect Formation and Electron Trapping in Oxides*
A study on the dynamic energy redistribution and statistics of charged defects in oxide materials.

B.Sc. North Carolina State University, Raleigh NC, Physics, 1985

1.3 Academic Experience

Timeline	Position	Institution
2010 - present	Professor of Physics	Department of Physics Wake Forest University, Winston-Salem NC 27109
2003 - 2010	Associate Professor of Physics Director: Center for Nanotechnology and Molecular Materials Tenure awarded in <i>Department of Physics</i>	
2009 - present	Adjunct Associate Professor of Cancer Biology	Wake Forest University School of Medicine, Winston-Salem NC 27157
2003 - present	Adjunct Associate Professor of Biomedical Engineering	WFU-VT School of Biomedical Engineering and Sciences Wake Forest University Health Sciences, Winston-Salem NC 27157
2002 - 2003	Associate Professor of Materials Science	Department of Physics and Astronomy Clemson University, Clemson SC
2001 - 2002	Associate Professor of Physics Tenure awarded in <i>Department of Physics</i>	
1997 - 2001	Assistant Professor of Physics	
1995 - 1997	Research Associate	Max-Planck-Institut für Metallforschung Institut für Werkstoffwissenschaft Stuttgart Germany
1993 - 1995	Postdoctoral Research Associate	Dept. of Materials Science and Engineering, University of Pennsylvania, Philadelphia PA
1994	Guest Researcher	Max-Planck-Institut für Metallforschung Institut für Werkstoffwissenschaft Stuttgart Germany

1987 - 1992	Graduate TA/RA (joint appointment)	Department of Physics Wesleyan University, Middletown CT
1987 - 1989	Observational Astronomer	Van Vleck Observatories, Wesleyan University, Middletown CT
1985 - 1987	Graduate RA/TA (joint appointment)	Department of Physics University of Rhode Island, Kingston RI
1983 - 1985	Undergraduate TA (physics)	Department of Physics North Carolina State University, Raleigh NC
1984 - 1985	Lab instructor (Astronomy Labs)	
1981 - 1982	Undergraduate Research Assistant	

1.4 Corporate Experience

Timeline	Company	Role
2001 - 2003	<i>Tetramer Technologies LLC</i> , Pendleton , SC	Founding member, technical advisor, board member
2001 - 2004	<i>NanoTechLabs LLC</i> Pendleton SC (re-incorporated in NC 2004 same name)	Founding member, technical advisor, board member
2007 - 2011	<i>PureLux Inc.</i> PTRP Winston-Salem NC	Founding member, technical advisor
2007 - 2010	<i>FiberCell LLC</i> Winston-Salem NC	Founding member, technical advisor
2011 - 2013	<i>Camel City Solar</i> . Philadelphia PA	Founding member, technical advisor
2011 - 2013	<i>CeeLite Inc.</i> Philadelphia PA	Technical Advisor
2012 - 2020	<i>Orthovative Technologies</i> , Winston-Salem NC	Technical Advisor
2013 - 2019	<i>VF Corp.</i> Burlington NC	Technical Advisor
2014 - 2020	<i>Ljus Inc.</i> Winston-Salem NC	Founding member, technical advisor, board member
2022 - present	<i>Quoherent Inc.</i> Huntsville AL	Founding member, tech advisor

1.5 Visiting Positions / Guest Scientist

Timeline	Institution	Role
1998	Hiroshima University (Higashi-Hiroshima Japan)	Scientist
1998	Max-Planck-Institut für Festkörperforschung (Stuttgart Germany)	Scientist
1999	Max-Planck-Institut für Festkörperforschung (Stuttgart Germany)	Scientist
1999	Max-Planck-Institut für Metallforschung (Stuttgart Germany)	Scientist
2000	Max-Planck-Institut für Festkörperforschung (Stuttgart Germany)	Scientist
2001	NIST Gaithersburg MD	Scientist
2001	Max-Planck-Institut für Festkörperforschung (Stuttgart Germany)	Scientist
2005	Kunming Institute of Physics (Kunming China)	Lecturer
2007	Massey University (New Zealand)	Lecturer

1.6 Consulting Work

Client	Date	Purpose	Outcome
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Maxeon	2024	Patent Review - Infringement	Ongoing
Stanford University	2018	Patent Review - Infringement	No litigation
University of Florida	2016	Patent Review - Validity	Proceeded with Patent
Glaxo-Smith Kline	2015	Portfolio Review	
Cook Medical	2008	Technology Review	
Yazaki Meter Corp.	2001 - 2004	OLED technology Review	

2. AWARDS and HONORS



2024	Fellow of the International Association of Advanced Materials (Europe)
2013	Fellow of the American Physical Society
2012	Editor in Chief of the Journal of Biosensors and Bioelectronics (OMICS Group)
2012	Faculty research award: "Most prolific inventor" WFU
2010	Editor in Chief of the journal <i>Engineering</i> , Scientific Research Publishers
2009	Editorial Board of <i>Engineering</i> Scientific Research Publishers
2009	Editorial Board of the journal <i>Current Organic Synthesis</i> Bentham Science Publishers
2007	Fellow of the Society for Nanoscience and Nanotechnology (Europe)
2001	<i>Sigma Xi Young Investigator Award</i> Clemson University
2001	<i>Outstanding Faculty Research Award</i> Clemson University
1986	Inducted into <i>Sigma Xi</i> (Wesleyan)
1985	Inducted into <i>Sigma Pi Sigma</i> (NCSU)
1984	Vice President of Society of Physics Students NCSU

3. PRODUCTS of SCHOLARSHIP



A selection of journal/book covers from the Carroll Research Group

3.1 Metrics and Impacts

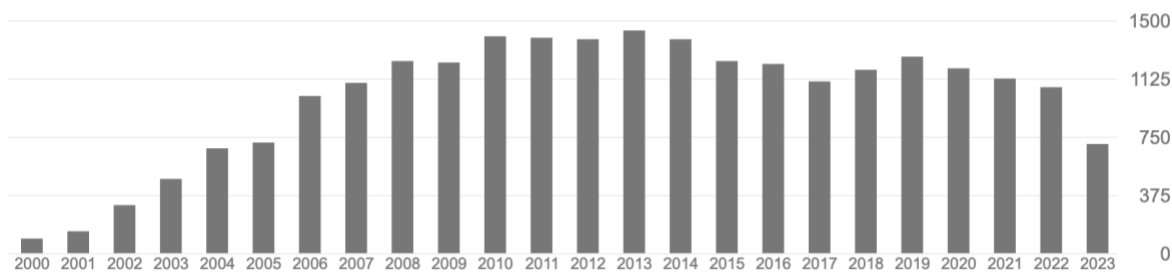
Publication analytics are derived from Google Scholar. GS entries are checked against WoS (ISI-indexed pubs from 1990 onwards) and ResearchGate. The Google Scholar is not a complete record of all publications. Data reflects reporting up to Sept. 2023.

From Google Scholar (August 2023)

Cited by	VIEW ALL	
	All	Since 2018
Citations	24489	6559
h-index	73	43
i10-index	215	118

Publications from the Carroll Group have been reprinted or cited in scientific “highlight” aggregators > 30 times. Articles have been reprinted or commented on in: *Science and Technology Alert, Nanowerks, Nanotech Web, Science, Advanced Materials, New Scientist, Physics Today, Scientific American, MRS Bulletin among others...*

Citations average > 1000 cites/year. The move to WFU was in 2003.



From Google Scholar (August 2023)

3.2 Books and Book Chapters

1. Introduction to Quantum Materials, Authors S. Roth, D.L. Carroll, V. Krstic, VCH-Wiley Press Weinheim Germany (2024)
2. Foundations of Solid State Physics, Authors S Roth and DL. Carroll, VCH-Wiley press Weinheim Germany (2020)
3. One-Dimensional Metals: 2nd edition Authors, S. Roth and D.L. Carroll, VCH press Weinheim, Germany (2009)
4. One-Dimensional Metals: Physics and Materials Science 3rd edition. Authors, S. Roth and D.L. Carroll, VCH -Wiley press Weinheim, Germany (2016).
5. Nanotube based Devices, Volume 722, MRS Symposium Proceedings, Ed. P. Bernier, D.L. Carroll, G. -T. Kim, S. Roth, MRS press, Pittsburg PA (2003)
6. Functional Carbon Nanotubes, Volume 858E, MRS Symposium Proceedings, Ed. D.L. Carroll, B. Weisman, S. Roth, A. Rubio, MRS Press, Pittsburg PA (2004)
7. Negative Index of Refraction: Optics and Metamaterials, J.E. Kielbasa, D.L. Carroll, and R.T. Williams in Optical Properties of Condensed Matter and Applications, Jai Singh (Editor) Wiley Press, Hoboken, NJ, (2006)
8. Bi-Functional Nanomaterials for the Imaging and Treatment of Cancer, A. Burke, D. Carroll, F. Torti, and S.V. Torti, Handbook of Nanoscience and Nanotechnology, Sonke Adlung (Editor) Oxford University Press, (2008)
9. Graphene—Conjugated polymer matrix composites, IJ Gray, DL Carroll, S Roth, *Graphene*, Editors: Viera Skakalova, Alan Kaiser, Elsevier publishing NY p. 439-457 (2021)
10. The rise of graphene in carbon thermoelectrics, DL Carroll, S Roth, G Marcus, *Graphene*, Editors: Viera Skakalova, Alan Kaiser, Elsevier publishing NY p. 143-174 (2021)
11. Introduction to physics of low-dimensional systems, S Roth, DL Carroll, *Graphene*, Editors: Viera Skakalova, Alan Kaiser, Elsevier publishing NY p. 1-12 (2021)

3.3 Significant Refereed Publications

1990 - 1996

1. M. Wagner, D.L. Carroll, D.A. Bonnell, and M. Rühle, "Nanoscale Metal-Transition Metal Oxide Interfaces Studied With Scanning Tunneling Microscopy (STM) and Scanning Tunneling Spectroscopy (STS)" *Electron Microscopy* (1996) 33 - 38.
2. M. Wagner, D.L. Carroll, D.A. Bonnell, and M. Rühle, "Charakterisierung vom Metall-Keramik-Grenzflächen mit Hilfe der Raster-Tunnel-Mikroskopie und Raster-Tunnel-Spektroskopie" Tagungsband zur Werkstoffwoche '96 (1996) 75 - 79.
3. D.A. Bonnell, B. Huey, and D.L. Carroll, "In Situ Measurement of Electric Fields at Individual Grain Boundaries in TiO₂" *Solid State Ionics* 74, (1995) 35-42.
4. D.A. Bonnell, Y. Liang, and D.L. Carroll, "On the Use of Electron Tunneling to Investigate Surface Structure and Interface Formation in Transition Metal Oxides: SrTiO₃ and TiO₂" *Interface Science* 2, (1995) 365-372.

5. T.W. Mercer, D.L. Carroll, Y. Liang, J. DiNardo, and D.A. Bonnell, "Photo-Induced Scanning Tunneling Microscopy of Insulating Diamond Films" *J. Appl. Phys.* 75, (1994) 12 - 18.
6. Y. Liang, D.L. Carroll, D.A. Bonnell, "STM Studies of Ultra-Thin Overlayers of Cu on SrTiO₃ (001) Surfaces" *J. Vac. Sci. Technol. A* 13 (1994) 2370 - 2390.
7. D.L. Carroll, Y. Liang, and D.A. Bonnell, "Investigation of the Growth and Structure of Aluminum Overlayers on TiO₂ (100) by Scanning Tunneling Microscopy" *J. Vac. Sci. Technol. A* 13, (1994) 2298-2303.
8. D.L. Carroll, D.L. Doering, and P. Xiong-Skiba, "Electron Trapping Mechanisms in an Electron Irradiated Single Crystal of SiO₂" *J. Vac. Sci. Technol. A* 11, (1993) 2312-2317.
9. D.L. Carroll, D.L. Doering, and B.S. Blais, "Thermally- and Optically-Stimulated Exoelectron Emission from an Electron Beam Irradiated Glass-Ceramic" *J. Vac. Sci. Technol. A* 10, (1992) 2863-2868.
10. P. Xiong-Skiba, D.L. Carroll, and D.L. Doering, "Characterization of Electron Beam Damage in Oxidized Silicon Using Thermally-Stimulated Exoelectron Emission" *J. Vac. Sci. Technol. A* 8, (1990) 1549-1554.
11. **P** Nanoscale Metal-Transition Metal Oxide Interfaces Studied with STM and STS
M. Wagner, D. L. Carroll, D. A. Bonnell and M. Rühle, Proc. 11th European Congress on Electron Microscopy, Ed. U.C.D. Belfield, (Dublin, Ireland 1996)
12. **P** Y. Liang, D.L. Carroll, and D.A. Bonnell, "The Morphology of Cu Clusters on SrTiO₃ (001) at Initial Stages of Metal Film Growth" Structure and Properties of Interfaces in Ceramics, editors: D.A. Bonnell, U. Chowdhry, and M. Rühle, Materials Research Society Vol 355, (1995) 51-7.
13. **P** D.A. Bonnell, D.L. Carroll and Y. Liang, "Initial Stages of Metal Film Growth on Transition Metal Oxides" Evolution of Thin Film and Surface Structure and Morphology, editors: B.G. Demczyk, E. Garfunkel, E.D. Williams, B. Clemens, and J. Cuomo, Materials Research Society, (1995) 130 - 134.
14. **P** B. Huey, D.L. Carroll and D.A. Bonnell, "Observation and Characterization of Electric Fields at Grain Boundaries" Structure and Properties of Interfaces in Ceramics, editors: D.A. Bonnell, U. Chowdhry, and M. Rühle, Materials research Society (1994) 401-405.
15. **P** D.L. Carroll, T. Mercer, Y. Liang, J. DiNardo and D.A. Bonnell, "Surface Morphology of Diamond Thin Films Using Photo-Induced Scanning Tunneling Microscopy" Determining Nanoscale Physical Properties of Materials by Microscopy and Spectroscopy, editors: M. Sarikaya, M. Issacson, and H.K. Wickramasighe, Materials Research Society, (1994) 483-487.
16. **P** P. Xiong-Skiba, D.L. Carroll, and D.L. Doering, "Defects Induced by Electron Bombardment and Substrate Doping in SiO₂ Thin Films" Amorphous Thin Insulating Films, editors: J. Kanicki, R.A.B. Devine, W.L. Warren, M. Matsumura, Vol. 284, Materials Research Society (1993) 23 - 27.
17. **P** D.L. Doering, K. Siek, P. Xiong-Skiba, and D.L. Carroll, "Defect Engineering and Characterization in Oxide Surfaces using Electron Beam Irradiation" Proceedings of the Materials Research Society Fall meeting (1993) 54 - 58.
18. **P** D.L. Carroll, P. Xiong-Skiba, and D.L. Doering, Photoemission in an electron Bombarded Glass-Ceramic" Phase Formation and Modification by Beam-Solid Interactions. editors: G.S. Was, L.E. Rehn, D. Follstaedt, Vol. 235, Materials Research Society, (1992) 395-399.
19. **P** D.L. Carroll, P. Xiong-Skiba, and D.L. Doering, "Defect Creation and Electron Trapping in Ceramic and Single Crystal Alumina by Electron Beam Irradiation" Beam-Solid interactions: Fundamentals and Applications, editors: L.R. Harriot, N. Herbots and R.S. Averback, Vol. 279, Materials Research Society, (1993) 445 -449.
20. **P** D.L. Carroll, P. Kinlen, S. Raman, P. Redlich, M. Rühle, X. Blase, J. Charlier, S. Curran, S. Roth, P.M. Ajayan, "Boron doped nanotubes: density of states from tunneling spectroscopy" Molecular Nanostructures, Proceedings of the International School on Electronic Properties of Novel Materials 11th Kirchberg Conference (1998) AIP publishing (**invited**)
21. **P** S. Curran, D.L. Carroll, S. Roth, P. Kinlen, S. Raman, P. Redlich, M. Rühle, P.M. Ajayan, "STM manipulation of individual carbon nanotubes" Molecular Nanostructures, Proceedings of

the International School on Electronic Properties of Novel Materials 11th Kirchberg Conference (1998) AIP publishing (invited)

22. P S. Curran, P. Ajayan, D.L. Carroll, J. Coleman, A. Dalton, W. Knechtel, B. McCarthy, W. Blau, "Doping of PPV with Carbon Nanotubes", Proceedings of the ICSM (1998) 7/98

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23. M. Wagner, T. Wagner, D.L. Carroll, D.A. Bonnell, and M. Rühle "Model Systems for Metal-Ceramic Interfaces", *Materials Research Society Bulletin*, 22, August (1997) 42-48 (invited).
24. A. Reçnik, D.L. Carroll, K.A. Shaw, D. M. Lind, and M. Rühle "Structural Characterization of Fe₃O₄-NiO Superlattices using High Resolution TEM", *J. Mater. Res.*, 12, No. 8 (1997) 2143-2151.
25. D.L. Carroll, P. Kinlen, S. Raman, P. Redlich, M. Rühle, X. Blasé, J.C. Charlier, S. Curran, S. Roth, and P.M. Ajayan, "Boron-Doped Nanotubes, Density of States from Tunneling Spectroscopy" *Molecular Nanostructures*, ed. H. Kuzmany, World Scientific Publishers, NY NY, (1997) 134 - 137.
26. S. Curran, P. Kinlen, S. Raman, D.L. Carroll, P. Redlich, M. Rühle, X. Blasé, J.C. Charlier, S. Roth, and P.M. Ajayan, "STM Manipulation of Individual Carbon Nanotubes" *Molecular Nanostructures*, ed. H. Kuzmany World Scientific Publishers, NY NY, (1997) 246 - 249.
27. D.L. Carroll, Ph. Redlich, P.M. Ajayan, J.C. Charlier, X. Blasé, A. De Vita, and R. Car, "Electronic Structure and Localized States at Carbon Nanotube Tips" *Physical Review Letters*, 78, No. 14 (1997) 2881.
28. D.L. Carroll, M. Wagner, M. Rühle, and D.A. Bonnell, "Schottky Barrier Formation in Nanoscale Contacts" *Physical Review B* 55 (1997) 9792-9799.
29. D.L. Carroll, M. Wagner, M. Rühle and D.A. Bonnell, "The Thermal Stability of Thin Copper Films Deposited on TiO₂ (110) Studied by Scanning Tunneling Microscopy" *J. Mar. Res.* 12 (1997) 975-983.
30. P Mercer, T. W.; Carroll, D. L.; Liang, Yong; Bonnell, D.; Friedmann, T. A.; Siegal, M. P.; Dinardo, Scanning tunneling microscopy and atomic force microscopy of chemical-vapor-deposition diamond and diamond-like carbon thin films. N. J. Editor(s): Cohen, Samuel H.; Lightbody, Marcia L. At. Force Microsc./Scanning Tunneling Microsc. 2, [Proc. U.S. Army Soldier Syst. Command, Natick Res., Dev. Eng. Cent. Symp.], 2nd (1997), Meeting Date 1994, 53-58. Publisher: Plenum, New York, N. Y

1998

31. D.L. Carroll, S. Curran, P. Redlich, P.M. Ajayan, S. Roth, M. Rühle "Nano-Domain Formation in B-Doped Carbon Nanotubes", *Physical Review Letters*, 81, No. 11, (1998) 2332-2335
32. S. Curran, D.L. Carroll, P. Redlich, P.M. Ajayan, S. Roth, M. Rühle "Picking a Needle from the nano-Haystack", *Advanced Materials*, 10, No. 7 (1998).
33. D. A. Bonnell, Y. Liang, M. Wagner, D. Carroll, M. Rühle " Effect of Size Dependent Interface Properties on Stability of Metal Clusters on Ceramic Substrates", *Acta Met* 46 (1998) 2263-70.
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2023 (focus on patent filings)

290. Incorporation of Stokes shifting dyes into a Si-based photovoltaic thermal system, IJ Gray, D Buna, KB Ucer, DL Carroll MRS Bulletin, 1-10 (2023)

2024

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P = refereed proceedings,

3.4 Patents

Only *ISSUED U.S. patents are listed*. Many are filed internationally as well, though the patent strategy is different for each one. In 2008 *Nanotechnology Law & Business* named **US7265174 B2** one of the most important patents in Nanotechnology world-wide. It is currently licensed and generates a royalty stream as are several others listed.

2023

1. Thin-film pn junctions and applications thereof
D Carroll
US Patent 11,678,496
2. Nanocomposite comprising semiconductor and metal nanoparticles, and assemblies
DL Carroll, DUN Chaochao, C Hewitt, R Summers
US Patent 11,631,795
3. Topological quantum computing components, systems, and methods
DL Carroll, AJ Reich, R Di Salvo
US Patent 11,580,437

2022

4. ION separation media and applications thereof
DL Carroll
US Patent 11,278,863

2021

5. Thin-film PN junctions and applications thereof
D Carroll
US Patent 11,101,439

2020

6. Thermoelectric apparatus and applications thereof
DL Carroll
US Patent 10,868,077
7. Thermoelectric apparatus and articles and applications thereof
DL Carroll, R Summers
US Patent 10,840,426
8. Devices and methods for treating spinal cord tissue
LC Argenta, DL Carroll, NH Levi, J Liu, MJ Morykwas, S Tatter
US Patent 10,632,235
9. Optoelectronic devices and applications thereof
DL Carroll
US Patent 10,566,536
10. Phase separated composite layers and applications thereof
D Carroll
US Patent 10,547,006

2018

11. Apparatus and method for cardiac tissue modulation by topical application of vacuum to minimize cell death and damage
LC Argenta, DL Carroll, NH Levi, MJ Morykwas, JE Jordan, WD Wagner
US Patent 10,076,318

12. Frequency dependent light emitting devices
D Carroll, R Summers, Y Chen
US Patent 9,905,810

2017

13. Light emitting device comprising conjugated terpolymer/teroligomer capable of white light emission
DL Carroll
US Patent 9,728,725
14. Low band gap conjugated polymeric compositions and applications thereof
N Levi, DL Carroll, C MacNeill, E Graham
US Patent 9,679,672
15. Small-scale pressure sensors
DL Carroll, FM Coldren, NH Levi, LX Webb, WD Wagner, TL Smith
US Patent 9,671,301

2016

16. Strain gauge and applications thereof
DL Carroll, T O'gara, T Smith
US Patent 9,464,948
17. Field induced polymer electroluminescent (FIPEL) device
DL Carroll
US Patent 9,318,721
18. Apparatus and method for cardiac tissue modulation by topical application of vacuum to minimize cell death and damage
LC Argenta, DL Carroll, JE Jordan, NH Levi, J Liu, MJ Morykwas
US Patent 9,289,193

2015

19. Composite organic materials and applications thereof
DL Carroll
US Patent 9,105,848

2014

20. Photovoltaic device with frequency conversion region
DL Carroll
US Patent 8,861,921
21. Devices and methods for treating spinal cord tissue
LC Argenta, DL Carroll, NH Levi, J Liu, MJ Morykwas, S Tatter
US Patent 8,834,520
22. Fiber photovoltaic devices and applications thereof
SA Curran, DL Carroll, JL Dewald
US Patent 8,772,629
23. Device and method for treating central nervous system pathology

LC Argenta, DL Carroll, NH Levi, MJ Morykwas, SB Tatter, WD Wagner
US Patent 8,764,794

2013

24. Organic optoelectronic devices and applications thereof
DL Carroll, J Liu, MAG Namboothiry
US Patent 8,558,105
25. Compositions and methods for treating cancer
DL Carroll, JH Stewart IV, NH Levi
US Patent 8,501,233
26. Solid state lighting compositions and systems
DL Carroll, MAG Namboothiry
US Patent 8,476,82

2012

27. Device and method for treating central nervous system pathology
LC Argenta, DL Carroll, NH Levi, J Liu, MJ Morykwas, S Tatter, ...
US Patent 8,267,960
28. Hyperthermic technologies and therapeutic uses thereof
S Torti, F Torti, DL Carroll, S Akman, O Nalamasu, P Ajayan
US Patent 8,252,772

2010

29. Halogen containing-polymer nanocomposite compositions, methods, and products employing such compositions
D Carroll, J Ballato, S Foulger, R Czerw, D Smith, H Shah, E Wagener
US Patent 7,834,077

2007

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D Carroll, J Ballato, S Foulger, R Czerw, D Smith, H Shah, E Wagener
US Patent 7,750,071
31. Halogen containing-polymer nanocomposite compositions, methods, and products employing such compositions
D Carroll, J Ballato, S Foulger, R Czerw, D Smith, H Shah, E Wagener
US Patent 7,265,174
32. Plasmon-photon coupled optical devices
J Ballato, DL Carroll, JR Dimaio
US Patent 7,206,114

2006

33. Plasmon-photon coupled optical devices
J Ballato, DL Carroll, JR Dimaio
US Patent 7,110,154

2005

- 34. Optical fiber amplifier with fully integrated pump source
J Ballato, DL Carroll
US Patent 6,947,208

2004

- 35. Nanostructured-doped compound for use in an EL element
R Czerw, D Carroll, S Hoshi
US Patent 6,833,201

3.5 Sponsored Programs

3.5.1 Funding profile

Fields of funding: nanosciences / materials physics / quantum materials and organic electronics.

Average annual expenditures for career: > \$500K/an.

Most relevant federal sources of funding: NSF, NIH, NASA, DOE, AFOSR, SOCOM, ARO, DARPA.

Industrial sources: (startups) Ceelite, Ljus, Fibercell, Nanotechlabs, (established) Foster-Miller, Magna, and Streamline Automation.

3.5.2 Sponsored Research Projects (up to close of 2022)

Total grant amounts are given and some include multiple-PIs. Thus, the total awards and the total expenditures are different.

Summary (Est.)

Total awards > \$ 29 million

Total expenditures at WFU > \$ 16 million

Total equipment assets in replacement costs ~ \$ 11 million (donations and gifts)

Average cost per paper ~ \$60,000 (based on expenditures)

Average cost per patent ~ \$458,000 (based on expenditures)

Table

Title	Date of Award	Sponsor	Co-I's	Amount (\$)
Electron Holography	1998	Ryobi Corp	none	5,000
The Foundations of Nano-Electronics	1997	Clemson University URG	none	3,000
Nanocomposite Materials for Aeronautics and Space Applications	2000	NASA-EPSCOR	Y.P. Sun	34,111
Materials and Devices for Optical Sources and Protection of Optical Sensors	1999	DARPA	B. Schwartz J. Ballato D. Zumbrennen E. Marotta	2,550,000
Novel Fluoropolymers and Carbon Nanotube Composites for Space Applications	2000	NASA South Carolina Space Grant Consortium	D. Smith	57,775
Metal-Ceramic Nano-Contacts: Towards New Nanocomposites	2000	South Carolina Research Initiative Grants (SCRIG)	none	80,000
Organic Nanocomposites for Large Area Displays	2000	Yazaki Corporation	none	286,000
Electronic Phenomena in Carbon Nanotubes: Quantum Mechanics in Low Dimensional	2000	NSF	none	291,000

Systems with Topological Complexity				
Si-Carbon Hybrid Nanocircuits for Robust Applications	2000	NASA	none	50,000
Nanomaterials with Novel Optical and Electronic properties	1999	NSF-EPSCoR	Ya-Ping Sun Shiou-Jyh Hwu D. Bruce M. Thies	500,000
Optical, Electronic, and Thermal Properties of Polymer Nano-Composites	1999	DEPSCoR-AFOSR	J.R. Manson T. Tritt	600,000
Near-Field Microscopy of Polymer-Based Nanocomposites	2000	AFOSR	J. Ballato	205,470
Advanced Photonic Materials Laboratory	2001	ARO/DARPA	J. Ballato D. Smith S. Foulger	3,000,000
Properties characterization of Torr-CP	2001	Elecon Inc.	none	40,000
Scale Hierarchy in charge transfer nanocomposites	2002	AFOSR	none	151,000
Color Agile Coatings	2002	Picatinny Arsenal	none	110,000
Robust Display Technologies	2002	DARPA	none	180,000
			Clemson Sub:	8,143,356
Agile Response Coatings	2004	Picatinny Arsenal	none	92,000
NSF NER	2005	NSF	Northeastern (Jackie Issacs)	30,000
Photovoltaics	2004	EIC	none	30,000
Surface Enhanced Raman	2004	EIC	none	30,000
Star Polymer OPV	2004	EIC	none	30,000
Scale Hierarchy in charge transfer nanocomposites	2004	AFOSR	none	453,000
Postdoctoral Fellowship	2004	ACS	Harrison	100,000
Agile Response Coatings	2005	AFOSR	S. Curran J. Reynolds T. Tiano G. McGuire	1,500,000
MURI Metamaterials for NIRs	2006	AFOSR	Peter Palfy	5,000,000 (our portion was 575,000)
GAC Cancer research	2006	GAC foundation	none	25,000
OREF	2006	OREF	L.X. Webb	100,000
CMRBC Breast Cancer grant	2006	ARO	none	100,000
EPA TiO2 study	2007	EPA	Richard Williams	20,000
EPA Toxicity study	2007	EPA	Amy Ringwood	200,000
FiberCell/plexilight	2007	Nanoholdings	none	773,034.00

Novel Organic Solar Cell technologies	2007	DOE	Richard Adams Catherine Murphy	500,000 (WFU)
FiberCell/purelux	2008	Nanoholdings	none	881,770.00
FiberCell/purelux	2008	Nanoholdings	none	23,586.00
CMBCR Breast Cancer grant	2008	ARO	none	100,000
Thai Government student fellowship	2008	Thai Government	none	15,000
NC Biotech Center Conference	2008	NC Biotech Center	none	10,000
NanoCancer Grant-Hyperthermia using NTs: R01 - (this was my program run through Cancer Biology where I am adjunct)	2009	NIH/NCI	Suzy Torti, PM Ajayan, Frank Torti, Robert Kraft, Steve Akman,	5,000,000 (This was conceived, all preliminary data taken, and written by NANOTECH. All money spent at WFU. Program managed by NANOTECH)
Stuttgart NanoDays grant	2010	Fraunhofer Institute (DE)	Siegmar Roth, Ivica Kolaric	50,000
Cook Medical: Distal tips of guide wires	2011	Cook Medical	none	50,000
Cross Campus: CM30 spectrometer	2011	Cross Campus Grant Foundation WFU	none	20,000
DataMax High resolution elemental Mapping	2011	DataMax Foundation	none	50,000
Stuttgart Nanodays Conference	2013	Fraunhofer Institute (DE)	Siegmar Roth, Ivica Kolaric,	50,000
Purelux Optimization	2010	PureLux, Inc.	none	23,543
PF-DT WOLED Development	2011 - 2013	CeeLite Technologies, LLC	none	708,246
FiberCell	2011	Camel City Solar	none	600,000
Organic Thermoelectrics: the matrix composite approach	2013	AFOSR	none	298,000
Power Generating Coverings and Casings	2013	NASA	none	60,000
Gammabrite	2013	Gammabrite	none	25,000
Nanosystems Engineering Research Center for Advance Self-Powered Systems of Integrated Sensors and Technologies	2013	NSF	none	198,000
HTC	2013	HTC	none	60,000
DragonSkin Development	2014	International ThermoDyne, LLC	none	250,000
Ljus Magna Development	2014	Ljus	none	250,000.00
Ljus OLEV	2014	Ljus	none	735,000.00
Phase I NASA	2014	Streamline/AFOSR	none	29,700.00
Partnership for Innovation: Accelerating Innovation Research - Technology Translation Graphenated-Carbon	2014	NSF	none	50,000.00

Nanotube (g-CNT) Composites for a Miniature, Fiber-Integrated Spectroscopy Light Source NSF				
Phase II NASA	2015	Streamline/NASA	none	350,000.00
Phase I ARO	2016	Streamline/ARO	none	48,000.00
Phase I NASA	2017	Streamline/NASA	none	40,000.00
Ultra High Performance Light Sources Based on Organics	06/01/2016	NSF	none	399,999.00
Exploring topological insulators for flexible/conf	08/15/2016	AFOSR	none	411,410.00
Pulsed Electromagnetic Field Therapy for Accelerated...	08/15/2017	ARO/WFUBMC	none	22,000.00
Phase I: Room Temperature Quantum	08/15/2019	Streamline/ DOD	none	10,000.00
Phase II: AFOSR	2019	Streamline/DoD	none	262,500.00
Phase II: Room Temperature Quant	03/01/2020	Streamline/ AFOSR	none	30,000.00
Phase I: Assembly of Topological Qubits int	04/15/2020	Streamline-DOD	none	10,000.00
PI Summer / Post doc 2022	06/01/2022	Streamline	none	111,888.00
Streamline / AFOSR: Phase II STTR Project	08/23/2022	AFOSR	none	249,962.00
Streamline	March 2024	Streamline/SOCOM	none	400,993.00
			WFU	Subtotal: 20,867,631.00
				WFU Sub 16,442,631.00
Totals				29,010,987.00

3.6 Scholarly Presentations

Presentations by myself and by my group are not tracked. Typically, I get far more requests to speak than I can accept. I average 3 to 4 invited presentations per year. The Carroll Group members typically contribute a presentation each at: MRS, APS, ACS, OSA or SPIE.

Partial Listing of Invited Presentations at MAJOR Conferences (updated 2014):

82. The Economist Meeting “Emerging Opportunities in Personal Power” Berkeley CA (03/14)
81. Winterschool on Novel Electronic Materials “Organic Thermoelectrics” Kirchberg Austria (03/14)
80. NanoCommercialization Conference “Innovation in Power Technology” (Keynote Address) Winston-Salem NC (03/13)
79. Stuttgart NanoDays “Closing Remarks: NanoCarbons” Stuttgart Germany (08/13)
78. AFOSR workshop on Organic Thermoelectrics, “Heterogeneity and Order in Organic Thermoelectrics,” Santa Barbara CA (07/13)
77. Villa Conference on Nanomaterials in alternative energy technologies, “Organic Thermoelectrics,” Orlando FL, (11/13)
76. Winterschool on Novel Electronic Materials “New Funding Models in Academia” Kirchberg Austria (03/13)
75. ONR/NSF Workshop on Organic Photovoltaics, “From Architectures to Morphology” DC (10/12)
74. NC Nanocommercialization Conference, “Solar: new approaches” Durham NC (04/12)
73. Villa Conference on Nanomaterials in alternative energy technologies, “Nanomaterials for 3D photovoltaic architectures,” Orlando FL, (04/12)
72. VF Futurewear conference, “electronic clothing” Winston-Salem NC (04/12)
71. NEW conference “Emerging Opportunities in Materials Sciences” Greensboro NC (10/11) **Keynote address**
70. International Conference on Nonlinear Materials “New Approaches to Organic Absorbers” Dublin Ireland (09/11)
69. MANCEF conference, Advances in Organic Photovoltaics” Greensboro NC (08/11)
68. Workshop on Alternative Energies, “Advances in Organic Photovoltaics” Oak Ridge TN (09/11)
67. Stuttgart NanoDays “Thermoelectric fabrics” Stuttgart Germany (08/11)
66. Workshop on Alternative Energies “3D photovoltaics” Oak Ridge National Labs Oak Ridge TN (09/10)
65. Stuttgarter NanoDays, “Novel carbon nanotube thermoelectric” Stuttgart Germany (08/10)
64. CARBIO conference on nanotubes in medicine, ‘Nanoparticle mediated cancer therapeutics” Dresden Germany (08/10)
63. Stuttgarter Nanodays, “Heterogeneous Dielectrics Using Nanocomposites” Stuttgart Germany (08/09)
62. SOPO, “Novel Architectures for Solar Collection”, Wuhan China (08/09)
61. American Chemical Society General Meeting “Nanocomposites for Display Applications” Salt Lake City UT (03/09)
60. Winterschool on Novel Electronic Materials “Imaging with a Negative Index Lens” Kirchberg Austria (03/09)

59. Organic Photovoltaics “Novel Geometries for Organic Photovoltaics” Barcelona Spain (12/08)
58. Renewable Energy 2008 “Novel Approaches to High Efficiency Organic Photovoltaics” Busan Korea (11/08)
57. Workshop on Organic Photovoltaics “Novel Nanocomposite approaches to High Efficiency Organic Devices” Oak Ridge National Labs (09/2008)
56. NC Nanotech “Novel Nanocomposite approaches to High Efficiency Organic Devices” Winston-Salem NC (03/2008)
55. Nanotec’08 “Novel Nanocomposite approaches to High Efficiency Organic Devices” Sussex UK (08/2008)
54. Nanobionics Workshop “Photodynamic Therapies based on carbon nanotubes” Wollongong AUS (06/2008)
53. Conducting Polymers, CNT Composites and Applications “Energy Transfer Mechanisms in Electroactive Nanocomposites” Chiang Mai Thailand (06/2008)
52. International Conference on Science and Technology of Synthetic Metals “Energy Transfer Mechanisms in Electroactive Nanocomposites” Brazil July 06-11, 2008
51. Nanomaterials for Defense Applications “Charge Transfer in electroactive nanocomposites” Washington DC (May 2008)
50. NANOTECH-2007 4th Topical Meeting on Nanostructured Materials and Nanotechnology “High Efficiency Solar Technologies” Monterrey MX (September 24-28, 2007)
49. NANOTECH-2007 4th Topical Meeting on Nanostructured Materials and Nanotechnology “Photodynamic Therapies based on carbon nanotubes” Monterrey MX (September 24-28, 2007)
48. NASATECH “High efficiency polymer solar cells” Boston MA (November 2007)
47. NANO TECHNOLOGY in Biology and Medicine “Photodynamic Therapies based on carbon nanotubes” Charlotte NC (Nov 2007)
46. NANOTECH2007 “High efficiency polymer solar cells” Monterrey, Nuevo Leon, Mexico (November 2007)
45. NANOTECH2007 “Photodynamic Therapies based on carbon nanotubes” Monterrey, Nuevo Leon, Mexico (November 2007)
44. 1st International Workshop on Frontiers in Organic Photovoltaics “High efficiency polymer photovoltaics” Seoul Korea (August 2007)
43. International Workshop on Conjugated Polymers “Carbon Nanotube Cancer Therapeutics” Wollongong Australia (Feb 2007)
42. Darpa Workshop on the future of Solar Energy “High Efficiency Organic Photovotlaics” Annapolis MD (Jul 2007)
41. Intertech Pira Workshop on Organic Solar Cell technologies “High Efficiency Polymer Solar Cells” Baltimore MD (April 2007).

- 40.** International Workshop on Conjugated Polymers “High efficiency Photovoltaics” Wollongong Australia (Feb. 2007)
- 39.** International Conference on Defects in Materials (ICDIM) “Negative Index Materials” Prague Czech Republic (June 2006)
- 38.** International Conference on Synthetic Metals “High efficiency Solar Cells” Dublin Ireland (June 2006)
- 37.** International Winter School “High Efficiency Solar Cells” Kirchberg Austria (March 2006)
- 36.** Optical Society of America “High Efficiency Solar Cells” Uncasville (CT) (April 2006)
- 35.** American Chemical Society (Colloid Section) “Colloidal Crystals with Conjugated Systems” Potsdam, NY (June 2005)
- 34.** Int. Conf. on Quantum Transport and Quantum Functional Materials “Advances in Organic Device Technologies” Bologna, Italy (June 2005)
- 33.** American Chemical Society “Applications of Iron Filled Nanotubes” San Diego, CA (April 2005)
- 32.** International Conference on Synthetic Metals “Advances in nanocomposite based devices” Wollongong, Australia (June 2004)
- 31.** American Physical society Regional Meeting “Advances in Organic Device Physics” Oak Ridge TN (Nov 2004)
- 30.** Optical Society of America, Optics in the Southeast “Optical limiting in carbon nanotubes and their variants” Charlotte, NC (Nov. 2004)
- 29.** Nanotec’ 04 “Advances in nanocomposite-based devices” Batz-Sur-Mer, France (Aug 2004)
- 28.** ISOPL (International Society for Optical Power Limiting) “Optical Limiting in Carbon Nanotubes: Materials Modifications” Tucson, Az. (April 2004)
- 27.** Herasus Workshop on Carbon Nanotubes “Charge Transfer Composites:advances in organic electronics” Bad Honnef, Germany (Oct. 2003)
- 26.** Nanotec’ 03 “Matrix nanocomposites for organic electronic applications” Sussex, England (Aug. 2003)
- 25.** SPIE/OSA “Organic photonics and nanocomposites” San Diego CA (Aug. 2003)
- 24.** American Ceramics Society (ACerS) “Boron Nitride Nanotubes” Nashville TN (April 2003)
- 23.** European Materials Research Society Meeting “Doping of carbon nanotubes” Strasbourg, France (June 2003)
- 22.** International School on Molecular Electronics “Advances in Boron Nitride Nanotubes” Kirchberg Austria (March 2003)
- 21.** SEAM conference (search for electroactive materials) “Nanocomposite technology for electro-optic applications” Brooklyn NY (12/08/2002)
- 20.** Int. Conf. on Quantum Transport in Synthetic Metals “Doping of Carbon Nanotubes” Seoul, Korea (05/08-10/2002)
- 19.** Society of Vacuum Coaters Meeting “Nonlinear optical applications of organic coatings” (07/18-21/2002)

- 18.** European Materials Research Society Meeting “Fluoropolymer Nanocomposites for Applications in Electro-actuation” Strasbourg, France (06/18-21/2002)
- 17.** American Physical Society March Meeting “Organic Light Emitting Diodes Based on Nanocomposites” Indianapolis, IN (03/18-22/2002)
- 16.** Winter School on Electronic Properties of Novel Materials “Transport Properties of Doped Carbon Nanotubes” Kirchberg, Austria (03/02-09/2002)
- 15.** IEEE Meeting “Nanocomposite Devices” Boulder, CO (01/09-12/2002)
- 14.** SPIE/OSA Pacific Rim meeting “Noise in nanocomposite devices” Adelaide, Australia (12/17-19/2001)
- 13.** Materials Research Society Fall Meeting “Optical Properties of Nanocomposites” Boston, MA (11/26-30/2001)
- 12.** The French-US workshop on Nanotechnology “Directions in Electro-Active Nano-composites” Montreal, Canada (10/25-28/2000)
- 11.** The Ga Tech workshop on Nano-science and Technology “N-doping of Carbon Nanotubes” Atlanta, GA (10/16-18/2000)
- 10.** SPIE-OSA meeting “Fluoropolymer Composites for Optical Applications” Charlotte, North Carolina (09/18-19/2000)
- 9.** South Eastern Sectional Meeting of the American Physical Society Meeting “Nanocomposites in Organic light Emitting Diode Technology” Chapel Hill, NC USA (11/08-10/1999)
- 8.** RAMNAS (sponsored by AFOSR) Dayton Ohio USA (10/26-29/1999)
- 7.** Swiss-US workshop on Nano-Science “Contact Potentials of Carbon Nanotubes” Zurich, Switzerland (09/19-23/1999)
- 6.** International Conference on Soft Materials Science “Low Current Imaging Techniques in Soft Condensed Matter” Tokyo, Japan (06/09-12/1999)
- 5.** European Conference on Nanostructures “Symmetry Breaking in Carbon Nanotubes” Sussex, England (09/08-11/1999)
- 4.** Engineering Foundation, Symposium on Nano-Composites “Optical and Transport Properties of Nanotube PMMA Composites” Anchorage, Alaska USA (04/10-14/1999)
- 3.** Engineering Foundation, Symposium on Nano-Composites “Tunneling Spectroscopy Studies of Nanotube PPV Composites” Anchorage, Alaska USA (04/10-14/1999)
- 2.** Materials Research Society Symposium Fall Meeting “Symmetry Breaking in Carbon Nanotubes” Boston, MA USA (12/1-5/1998)
- 1.** South Eastern Regional SPS Undergraduate Research Symposium “Raman Spectroscopy for Defect Identification in SiO₂” Boone, NC USA (11/1986)

Partial Listing of Invited Colloquia Presentations (updated 2014):

- 53.** “Organic Thermoelectrics” JSNN Colloquium, Greensboro NC (02/14)

52. “Emerging trends in Nanomaterials for Alternative Energy Applications” NCSU REU colloquium, Raleigh NC (06/12)
51. “Emerging Trends in Nanotechnology”, TIPS program colloquium, Duke University, Durham NC (04/11)
50. “Emerging trends in Materials Science” Forum for Interdisciplinary Research, NC A&T Greensboro (04/11)
49. “Nanocomposites for Solar Applications” Department of Chemical Engineering, NC State University (09/09)
48. “Nanocomposites for Solar Applications” Department of Physics, University of Wuhan (08/09)
47. “Photo-thermal therapeutics for Cancer treatments” Department of Natural Sciences Shaw University, Raleigh NC (11/08)
46. “Energy Transfer Mechanisms in Electroactive Nanocomposites” Department of Chemistry University of Mass. Amherst. (10/08)
45. “Energy Transfer Mechanisms in Electroactive Nanocomposites” Center for Advanced Photonics Engineering, Cambridge University U.K. (05/2008)
44. “Nanocomposite technologies for organic devices” AFOSR annual review (05/2008)
43. “Solar Technologies” Nanoholdings Inc. annual scientific meeting, Miami FL (11/2007)
42. “Lighting Technologies” Nanoholdings Inc. annual scientific meeting, Miami FL (11/2007)
41. “High efficiency Polymer Solar Cells” Department of Materials Science, MIT, (10/2007)
40. “Photo-thermal therapeutics for Cancer treatments” Department of Physics, Victoria University (NZ) (09/07)
39. “High Efficiency Solar Cells” Department of Chemistry, Massey University (NZ) (09/07).
38. “Photo-thermal therapeutics for Cancer treatments” Department of Chemistry, Ortaga University (NZ) (09/07)
37. “Photo-thermal therapeutics for Cancer treatments” Center for NanoSciences, Massey University (NZ) (09/07)
36. “High Efficiency Organic Photovoltaics” Department of Chemistry, Carnegie Mellon University (11/2006)
35. “High Efficiency Organic Solar Cells” Department of Chemistry, University of South Carolina (09/2006)
34. “Organic Devices based on Charge Transfer Nanocomposites,” Department of Materials Science, University of Connecticut (11/2004) (2003)
33. “Nanomaterials” Hanscom Airforce Base MA (08/2003)
32. “Charge Transfer Nanocomposites,” Department of Physics, Wesleyan University (12/2003)
31. “Charge Transfer Nanocomposites,” Department of Physics, North Carolina State University (10/2003)
30. “Charge Transfer Nanocomposites,” Department of Physics (Condensed Matter Seminar Series), University of North Carolina – Charlotte (9/2004)

29. "Nanotechnology: opportunities in advanced materials," Yazaki Technical Center, Susono City, Japan (6/2003)
28. "Charge Transfer Nanocomposites," Department of Physics (Condensed Matter Seminar Series), University of North Carolina - Chapel Hill (5/2003)
27. "Symmetry Breaking in Carbon Nanotubes," Department of Physics, Wake Forest University (11/2002)
26. "Nanocomposites," Department of Physics, University of South Carolina - Columbia (4/2002)
25. "Carbon Nanotubes: the next generation electronics," Dept. of Physics, University of Missouri Kansas City (12/2000)
24. "Symmetry Breaking in Carbon Nanotube Contacts," Universität Tübingen, Tübingen Germany (09/1999)
23. "Symmetry Breaking in Carbon Nanotube Contacts," Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany (09/1999)
22. "Symmetry Breaking in Carbon Nanotubes," NIST, Washington DC (07/1999)
21. "Symmetry Breaking in Carbon Nanotubes," Dept. of Physics, Western Carolina University (05/1999)
20. "Symmetry Breaking in Carbon Nanotubes," Department of Physics, University of South Carolina-Columbia (09/1998)
19. "Symmetry Breaking in Carbon Nanotubes," Department of Physics, University of North Carolina-Chapel Hill (08/1998)
18. "Optical and Transport Properties of Nanotube PPV Composites," Department of Applied Physics, Hiroshima University, Hiroshima Japan (08/1998)
17. "Optical and Transport Properties of Nanotube PPV Composites," Yasaki Corporation, Technology Development Center, Tokyo Japan (08/1998)
16. "Transport Phenomena in Nanoscale Contacts," Department of Materials Engineering, Rensselaer Polytechnic Institute Troy NY (11/1997)
15. "The Determination of Interfacial Optical and Transport Properties Using STM/STS," Department of Materials Science, Oxford University, Oxford, U.K. (07/1996)
14. "Determination of Local Density of States in TiO₂ supported Ultra-Thin Cu Overlayers using STM," Department of Physics, Queens University, Belfast, Northern Ireland (07/1996)
13. "Transport Phenomena in Nanoscale Contacts," Department of Physics, Clark University, Worcester MA (11/1996)
12. "Transport Phenomena in Nanoscale Contacts," Department of Physics, Worcester Polytechnic Institute, Worcester MA (11/1996)
11. "Transport Phenomena in Nanoscale Contacts," Department of Physics, University of Georgia, Athens GA. (11/1996)
10. "Schottky Barrier Formation and Transport Properties in Cu-TiO₂ Nano-Contacts," Max-Planck-Institut für Metallforschung, Institut für Werkstoffwissenschaft, Stuttgart, Germany (04/1996)

9. "Schottky Barrier Formation in Metal-Oxide Nanostructures Studied by STM," Department of Physics, Stevens Institute of Technology, Hoboken NJ (11/1995)
8. "Transport and Quantum Size Effects in Nano-Scale Contacts Studied by Scanning Tunneling Microscopy," Department of Physics, University of Exeter, Exeter, U.K. (11/1995)
7. "The Use of STM and Tunneling Spectroscopy in the Study of Supported Metal Nanostructures," Department of Physics, Wesleyan University, Middletown, CT (04/1995)
6. "Tunneling Microscopy and Tunneling Spectroscopy Applied to Wide Band-Gap Materials," Max-Planck-Institut für Metallforschung, Institut für Werkstoffwissenschaft, Stuttgart, Germany (10/1994)
5. "Defect Formation and Electron Trapping in Oxides due to Electron Beam Irradiation," Department of Materials Science and Engineering, University of Pennsylvania Philadelphia, PA (11/1993)
4. "Electron Trapping Mechanisms in Insulators and Wide Band-Gap Semiconductors Studied by Thermionic Emission, Cathodoluminescence and Photoluminescence," Department of Materials Science and Engineering, University of Pennsylvania Philadelphia, PA (12/1992)
3. "Electron Trapping Mechanisms in Insulators and Wide Band-Gap Semiconductors Studied by Thermionic Emission, Cathodoluminescence and Photoluminescence," Department of Physics, Wesleyan University, Middletown, CT (07/1992)
2. "Chemisorption on Metals with Modified or Incomplete Band Structure," Department of Physics, Wesleyan University, Middletown, CT (02/1990)
1. "Final State Effects in Electron Stimulated Desorption Ion Angular Distributions (ESDIAD)," Department of Physics, Wesleyan University, Middletown, CT (02/1988)

4.0 TEACHING and MENTORING

4.1 Statement of Teaching

I have taught physics courses since 1997 and tried many different approaches and methods. Some of these worked and some did not. This is what I have learned works for me.

1. **Define your outcomes:** Learning is defined differently by everyone. It can mean anything from the ability to regurgitate facts, to the ability to use specific skills in specific circumstances. My definition states that “something has been learned when a specified set of facts and concepts can be correctly applied in circumstances not envisaged by the presentation of those facts and concepts.”
2. **No multimedia teaching:** Students respond positively to and prefer the use of computers in their learning process. Zoom, Canvas, iphone, online instant feedback... However, they inevitably learn less when computers and multimedia are involved. I avoid the use of all entertainment related media in teaching when possible. My teaching is a relationship between humans. Computers are to be used only as computational aids in problem solving.
3. **Tutorials are essential:** Lectures are for presentation of ideas. Tutorials are for learning how to put ideas to use: the math, the setup, the follow through of a problem. The Ox-bridge tutorial method mixes lectures with small group problem solving discussion/work sessions. It is the most effective way to communicate new ideas. It requires the tutorial instructors to be coordinated with the lecturer.

4.2 A Listing of Courses

Clemson

PHYS 207/208 These are noncalculus-based courses covering mechanics, thermodynamics, and electricity and magnetism. Required for Premed/Nursing/Architecture. Aside from standard lectures, these courses offer evening problem recitation for students. Enrollment typically exceeds 100. (CLEM)

PHYS 122 Engineering service course that is taught using calculus. Required for all engineering majors. Standard lectures were developed as well as problem sessions. In this course a new approach to “Critical Learning” was taken that focused on using the similarities between homework problems to attack more unfamiliar or unconventional problems. Course evaluations along with test performance seem to indicate this approach meets with success in a larger fraction of the students than conventional “lecture-homework-test” scenarios. Enrollment generally exceeds 100. (CLEM)

PHYS 325/326 Junior Lab. is a laboratory based physics course required for majors. Covers data analysis, statistics, experimental technique. This course was completely redesigned over the year to modernize the concepts and bring it in line with other elements of our curriculum. New equipment was added along with more advanced microscopy techniques utilizing central facilities. (CLEM)

PHYS 845/846 Graduate Condensed Matter Physics is the highest level condensed matter course offered by the department. It is strongly encouraged for graduate students in condensed matter and had not been taught regularly for some time. Within the past two years, I have revamped the course and student enrollment each year has been around 10-15. This is quite large for such an advanced course. (CLEM)

PHYS 875 (Polymer) Generally taught as a seminar course, over the last two years I have used this course for the development of a polymer-physics sequence. It has been well attended by students from physics, materials science, polymer science, and chemistry. The course is intended to be integrated into the graduate materials science curriculum as an elective and provide a basis for multidisciplinary education between physics, materials, and polymer science. (CLEM)

PHYS 875 (NANO) This course has been taught several times and focuses on nano-sciences and characterization at the nano-scale. The lab section of the course offers the students hands on experience with AFM and STM along with calculational methods typically used in the probe microscopy field. This course has been recognized in an invited publication (*Journal of Nanoparticle Science and Technology*). It is opened to both graduate and advanced undergraduate students. (CLEM)

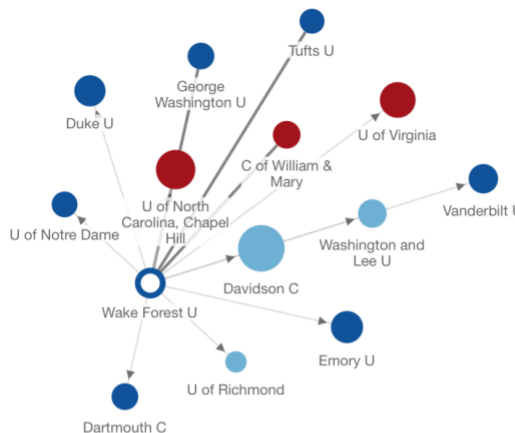
MS&E 811 *Materials Science and Engineering I: Structure, Bonding, and Synthesis* Fundamentals of materials science and engineering; crystal structures, chemical and atomic bonding, mechanical properties,

periodicity in relation to material engineering, methods of materials synthesis. *Preq:* BS degree in Materials Science and Engineering, Physics, Chemistry, or appropriate engineering discipline or consent of instructor. (CLEM)

MS&E 812 Materials Science and Engineering II: Electronic, Magnetic, Thermal, and Optical Properties of Materials Continuation of MS&E 811: electronic, magnetic, thermal, and optical properties of materials; structure/properties and application of metals, semiconductors, ceramics, and polymers and their importance in materials science and engineering. *Preq:* MS&E 811 or consent of instructor. (CLEM)

Wake Forest

Wake needs more courses: * WFU has strong similarity and overlap in student profile with Tufts, Vanderbilt, Emory, Duke, Dartmouth, Boston College, among others. For our physics program to be likewise competitive with these Universities, the breadth and depth of course offerings in the fields that overlap, should be roughly equivalent. WFU does offer the same core courses at the undergraduate and graduate level. However, a greater number of faculty generated “expertise courses” are needed to enhance the learning environment. **based on a 2023 survey of course offerings at these overlap schools.*



Wake Forest University

Winston-Salem, NC | Private Doctoral

13 colleges selected as peers by this college. 18 colleges selected this college as a peer. 3 peer colleges that also chose this college as a peer.

● University ● Peer institutions

Admissions Rate	25%	17%
Graduation Rate	90%	92%
Enrollment	8,076	12,146

PHYS 266 Intermediate Physics Lab. This course teaches elements of modern physics from an experimental/observational point of view. A set of modern experimental exercises are carried out. The course focuses on error analysis in the physics calculational sciences and has an important scientific writing component, components on plagiarism and laboratory safety, as well as a critical thinking component. I wrote the textbook used in the course presently and continue to make improvements in the text which is offered free of charge to WFU undergraduates. Since arriving at WFU, this course has been completely reworked and is taught with two graduate assistants to ensure safety. (WAKE)

***PHYS 337/637 Undergraduate level mechanics** focusing on Lagrangian and Hamiltonian Dynamics. The course usually has around ten students. Novel aspects of the course were the introduction of chaos theory, and continuum mechanics. (WAKE)

***PHYS 339/340 & 639/640 Undergraduate level electromagnetism** for majors. This course introduces rigorous E&M theory. A novel aspect of the course is its introduction of negative refractive index materials, and near-field optics. This course is also frequently used by graduate students to prepare for the doctoral qualifying exams. (WAKE)

**These core courses are taught using tutorial methods*

PHYS 354/654 Introductory solid-state physics. This is a survey course covering the basic principles of thermal, electronic, and optical properties of solids. This course typically is the first course taken in the preparation of a solid state physics concentration. Both graduate and undergraduate students typically take this course. (WAKE)

PHYS 356/656 Advanced Electron Imaging. This course was developed and taught for the first time in 2007. It is offered yearly and covers advanced topics in electron microscopy including high resolution techniques, microscope design, and includes a laboratory exercise using the microscopes of the NanoCenter. It is offered in addition to my usual course load (WAKE)

PHY 357/657 Scanning Probes: An introduction to the basic theory and practice of scanning probe microscopy. Both STM, and AFM are covered in the 1 semester course. Grades are derived only from lab write-ups. Full attendance is mandatory. (WAKE)

****PHY 345/645 Introduction to Quantum Computing.** This is Quantum Computing for Beginners is an introduction to the foundations and hardware of Quantum Computers It covers basic algorithms, the theory of Qubits and registers, gate structure, and the physical systems that have been achieved. Course format is lecture with a lab taught in Quiskit.

****PHYS 355/655 Exotic Materials.** This course is a lecture/seminar series course that meets twice each week and focuses on advanced topics in materials dimensionality, symmetry breaking and topology. It is an advanced condensed matter course for quantum materials (third condensed matter course in our sequence) and uses my textbook “Quantum Materials.” It is offered in addition to my usual course load and is offered every other year. (WAKE)

****PHY 391/691 Quantum Information Sciences.** This class is a one-semester graduate-level introduction to Quantum Information Theory, that is Shannon Theory and its extension to the quantum domain. This will include quantum communication channels (noiseless and noisy), different resources for communication (e.g., quantum communication, classical communication, and shared entanglement), basic families of quantum communication protocols, the definition of various channel capacities, quantum error-correcting codes, and experimental implementations. It is intended as a second semester to PHY 345: An Introduction to Quantum Computing. (WAKE) (a newly created course)

***These are core courses to the department's new quantum computing masters program*

PHY 754 Surface Science. This course is a lecture/seminar series course that focuses on modern methods of materials analysis using scanning Auger, XPS, and EDAX. It has a laboratory component using advanced instruments available at NanoCenter and is accessible to both undergraduate and graduate students with a background in quantum mechanics. It is taught in addition to my usual course load and is offered every other year. (WAKE)

PHYS 358/658 Kinetics. This new course was developed through a generous faculty sabbatical grant. It is a follow-on to traditional thermodynamics courses offered both in Physics and Chemistry and is accessible to both undergraduates and graduate students. Kinetics of Materials presents the fundamentals of non-equilibrium thermodynamics in solids. The basic theory of phase transitions, Onsager, and a number of exotic examples will be discussed. The course uses an open format. It was taught for the first time in the fall of 2014 and thereafter every other year as needed. It is taught in addition to my usual course load. (WAKE)

4.3 Testing Pedagogy

To align outcome metrics between learning definitions and testing modalities, exams should be multi-component in nature – testing different levels and types of understanding. In all core courses using

the tutorial teaching methods, I have constructed a set of cross-referenced question banks that are graded in terms of difficulty and learning type.

Example:

A 4 metric ton truck traveling at 40 km/hr. hits an oncoming 100 kg Vespa scooter traveling at 20 km/hr. Which vehicle experiences the greatest force?	We have already examined how to calculate the electric field along the axis of a ring of charge. Now we want to know the field along the axis of a round plate of charge of the same diameter.	Given that the sky is blue, calculate Avogadro's number. <i>(Also known as a minimum information problem)</i>	Essay: provided above is a reasonable model for how a magnetar might generate such huge magnetic fields. Using what we have learned so far, analyze this model to see if it makes sense and where it may fail.
This tests the understanding of a basic concept, in this case Newton's laws.	This tests application of analytical problem solving skills on problems of similar type.	This looks beyond the obvious application of a concept and mathematical skill set to see if the student has internalized the lesson.	This final component is a take home exam question intended to examine critical thinking and its utilization of new materials and models.
Mastery of the material at this level is required to achieve at least a C in the course.	Mastery of this skill is necessary to reach a level of B in a core class.	Mastery of materials at this level earns the student an A in core classes.	These questions are used in support of students advancing to the A level of the grading.

4.4 Summary of Teaching Novelty

In summary the novelty of my contribution of departmental teaching lies in three elements:

1. The use of Tutorial teaching methods.
2. The development of new courses and the regular teaching of those courses on top of regular teaching load.
3. Assembly of standard teaching assessments allowing for cross comparisons among different student groups.

4.5 Statement of Mentoring

In my research group, Undergraduate and Graduate Students are confronted with several expectations.

1. Students must be primarily autonomous in their work, defining for themselves the meaning and boundaries of that work. Within these boundaries, each thesis should have an experimental and theoretical component both led by the student and clearly demonstrate an understanding of where within the greater scientific effort their work lies.
2. Within the group there is a focus on scientific exchange through regular publication, using referee's comments to improve their approach and their writing/presentation. No fewer than ten (10) high quality publications are acceptable to receive a PhD. Exceptions to this rule are extremely rare.
3. Interactions within the scientific community should include exchange, collaboration, and conferences. This includes attending educational workshops and working with the many lab guests we have. Collaborative exchange is required for each student.
4. Graduate students must attend group workshops and seminars for formal presentation of advanced materials.

4.6 Graduate Research Student Listing (2023)

The rules of the Carroll Research Group are strict, they reflect the way I believe a PhD. should be prepared. Generally, there is plenty of support from myself, postdocs, and research faculty to help students

that struggle – and they should all struggle some.

PhD.	1 st appt.	MS	1 st appt.
D. Tekleab	Motorola	A. Date	OSRAM
S. Webster	University of Central Florida	P. Iyer	
R. Czerw	NANOTECH Labs	S. Xing	
Nicole Levi	WFUBMC plastics	W. Wang	Tetramer
Faith Coldren	UPENN	D. Weston	Michelin
Yuan Li	Company in China	Baxter McGuirt	Seminary
Wanyi Nie	LANL	Jillian Berjke	Michigan State
Corey Hewitt	Toyota Research	Eric Peterson	Law Firm in Winston
C.C. Dun	Berkeley	Robert Link	Private HS in NYC
Alex Taylor	University of Heidelberg	Eric Henderson	Coatings Company in Greensboro
Greg Smith	College of Charleston		
Wenxiao Huang	Stanford		
Junwei Xu	Stanford		
David Montgomery	Private High School in Asheville		
Gabriel Marcus	Grad. 2024		
Tim Carlson	Grad 2025		
Lindsey Gray	ORISE Postdoctoral Fellowship at the U.S. Department of Homeland Security Transportation Security Laboratory NJ		
Moti Mirhosseini	Grad 2026		

Of the group members Wanyi Nie, Nicole Levi, and Chaochao Dun have all gone on to tenure track positions at U.S. universities. Scott Webster is research faculty at UCF. All other PhDs are in corporate or government research labs with the exception of David Montgomery who teaches physics in HS.

It is expected that graduate students will spend some time in laboratories off campus. This requirement is waived under certain extraordinary circumstances. However, all recent graduate students have fulfilled this requirement. While this is somewhat unique to a U.S. laboratory it's quite common among leading European laboratories and it is this model we have adopted. Most students spend from 1 month to 6 months in exchange experience. Typically, this is done to augment measurement capabilities required for a specific thesis project.

* Wake Forest

* Clemson

4.7 Undergraduates in the Lab

Grace Yook Michael McCarthy Nathan Beetz	Jillian Berjke Michael Roman Alex Macropolis	C. Campbell J.R. Sharpe D. Tarbox
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Ryan Barbalance Kelli Simms Roland Carson Matthew Howell Nicholas Lepley Alex Taylor	Sara Sizemore Jay Patel T. Zimmerman Baxter McGuirt J. S. Clayton F. Coldren	E. Gregory D. I. Benenti Molly Binder Griffin Shoemaker Claire Griffin Alli Swight
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Undergraduates are also welcomed into the lab. These students typically do a senior thesis though some do not. A majority of students go to graduate school from our labs. Students join a subgroup specialty with graduate student and postdoctoral mentors for day to day work. This increases safety in the lab and ensures that no student feels isolated. Undergraduates must attend team meetings and activities weekly and are an equal part of the group with their own assignments.

Student exchange is an important part of the WFU experience, but one that many science majors have difficulty participating in due to class schedules. We provide summer study abroad opportunities that allow them to work at one of several exchange site. Most recently, 2 students worked at the University of Vienna with Prof. Skakalova using aberration corrected TEM to image Graphene. This instrument is one of only a few in the world with analytical capabilities and therefore represents a unique opportunity for our undergraduates to access such facilities. A number of labs have welcomed students from the Carroll group over the years. These laboratories include: University of Central Florida (CREOL) (US), Army Research Labs (US), MPI-Stuttgart (Germany), ORNL (US), Hiroshima University (Jap), RPI (US), Rice University (US), NIST (Gaithersburg) (US), Massey University (NZ), Streamline (US), Trinity College Dublin (IE), University of Madrid (Spain), FAU (Germany).

4.8 Visiting Scientists of the Carroll Research Group

Visitor	University	Country	Visitor	University	Country
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Auren Ferguson	Trinity College Dublin	Ireland	W. Blau	Trinity College Dublin	Ireland
Eamon Loughman	Trinity College Dublin	Ireland	S. Roth	MPI- FKF	Germany
Chanitpa Khantha	Chiang Mai	Thailand	P.M. Ajayan	RPI Troy NY	USA
Chanitpa Khantha	Chiang Mai	Thailand	T. Ebbessen	Universit�e Louis	France
V. Kruefu	Chiang Mai	Thailand	Zhouhang	Pasteur Strasbourg	
Aston Partridge	Massey University	New Zealand	Wang	RHK Technologies	USA
Damon Aboud	Waterloo University	Canada			
Chanitpa Khantha	Chiang Mai University	Thailand			
S. Phanichphant	Chiang Mai University	Thailand			
Sihai Chen	Corporate Affiliate	USA			
Paul Kane	Trinity College Dublin	Ireland			
Brian Steer	Trinity College Dublin	Ireland			
Piched Auragudom	Chiang Mai University	Thailand			
Orla Byrne	Trinity College Dublin	Ireland			
Fiona McGuire	Trinity College Dublin	Ireland			
J. Talla	New Mexico State University	USA			
Jayakanth	Indian Institute of Technology Delhi	India			
E. McGuire	Trinity College Dublin	Ireland			
D. Richter	Trinity College Dublin	Ireland			
J. Kim	Seoul National University	Korea			
J. Park	Seoul National University	Korea			
S. Vieira	Manchester University	UK			
H. Sakatoro	Yazaki Corporation	Japan			
J. Sheridan	Trinity College Dublin	Ireland			
Z. Guo	Chinese Academy of Sciences	China			
Y.-W. Park	Seoul National University	Korea			
L. Kish	Angstrom Laboratory Uppsala	Sweden			
B. Foley	Trinity College Dublin	Ireland			
K. Lee	KIST	Korea			
K. Kim	KIST	Korea			
B. Gersten	ARL Maryland	USA			
B. McCarthy	Trinity College Dublin	Ireland			
A. Strevens	Trinity College Dublin	Ireland			
L. Goldner	NIST Washington	USA			
Z. Zha	MPI- Festk�rperforschung	Germany			
E. Dusjardin	NEC Corporation Princeton NJ	USA			

The Carroll group maintains strong collaborative ties with laboratories across the world and is increasingly well-recognized as an excellent place to visit. Along with raising the visibility of the group, these programs create an atmosphere of *scientific excellence* for our students and postdoctoral fellows. Like the Max-Planck-Institute after which our program was styled, this creates a flow of ideas and approaches that make our laboratory an exciting place for scientists and engineers to come together to address the most pressing current problems in solid state physics.

Above is an incomplete list of visitors to the lab, there are many more but this gives an idea. Most stay for several months to several years depending on their institution.

4.9 Postdoctoral Mentoring

Another important aspect of a successful lab is the training and placement of postdoctoral associates. To date we have a 100% placement of PhD students and 100% placement of Postdoctoral fellows into research intensive environments. Of these 80% went into academic laboratories, the other 20% went into industrial or government labs. The result has been that we have added to WFU's increasing reputation as an excellent place to receive graduate and postdoctoral training.

4.10 Postdoctoral Fellows Listing

Dr. Yuan Li Dr. Corey Hewitt Dr. HuiHui Wang Dr. Jung Ho Park Dr. Wei Zhou Dr. Robert Coffin Dr. Yonghua Chen	Dr. S.-G. Lee Dr. H.-S. Woo Dr. J. Xu Dr. P. Yang Dr. S. Chen Dr. Benjamin Harrison Dr. Junping Zhang	Dr. Miru Haluska Dr. Scott Webster Dr. Marisol Reyes-Reyes Dr. Kyung Kon Kim Dr. M. Schmid Dr. J. Liu Dr. A.G. Manoj
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4.11 Summary of Novelty in Undergrad, Grad, and Postdoc Mentoring

The specific contributions I make to Mentoring and Research Student preparation lies in three parts:

1. Specific requirements on numbers and quality of publications and presentations to the scientific community to receive a degree. When leaving this group the student will know how to write and how to present their work.
2. Exchange and collaboration programs that are actively funded and sought out for the students by me to aid in the creation of a scientific world view that is broader than WFU. This more fully integrates the student into the wider scientific community.
3. The *at-home* experience that includes visiting scientists and required participation in home-based workshops, seminars, and classes broadens the student's capabilities in the lab or using computational techniques. There is at least one point of group participation each week.

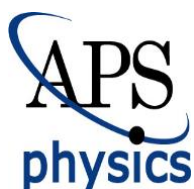
5.0 SERVICE

5.1 Metrics

Service is divided up into three parts: Service to the scientific community, Service to the University, and Service to the community at large. While there are very few ways to quantify the overall impact this may have on the university as a whole, certainly it should be expected that services both to the University and outside of the University should serve University interests positively.

5.2 Professional Service

Professional service includes activities that have helped to promote the fields of materials physics and nanoscience. Such activities are an indication of impact in the field outside of direct scholarship.



5.2.1 Organization/Chair of Major National & International Conferences (updated 2014)

Stuttgart NanoDays (Stuttgart Germany) International Organizing Committee	(2013)
RENET conference (Kerala, India) International Organizing Committee	(2012)
Stuttgart NanoDays 2011 (Stuttgart Germany) International Organizing Committee	(2011)
Stuttgarter NanoDays 2010 (Stuttgart Germany) International Organizing Committee	(2010)
Stuttgarter NanoDays 2009 (Stuttgart Germany) International Organizing Committee	(2009)
IASTED NANA 2008 (Crete Greece) International Organizer Committee	(2008)
Workshop on Nanomaterials in Hyperthermia (NC) Organizer	(2008)
IUMACRO-07, ACS conference on sustainable technologies (NY) Co-organizer	(2007)
Santa Fe Workshop on Advanced Materials (NM) Co-Organizer	(2005)
Materials Research Society Fall Meeting (nanotube applications symposium HH) Co-Organizer	(2004)
Workshop on Near-Field Microscopy (NC) Co-Organizer	(2004)
Materials Research Society Spring Meeting (nanotube devices symposium N) Co-Organizer	(2003)

SPIE meeting (San Diego) Co-Organizer	(2002)
SPIE meeting of the Pacific Rim (Adelaide, Australia) Co-Organizer	(2001)
Southeast Sectional OSA/SPIE meeting (Clemson, SC) Co-Organizer	(2001)
American Physical Society March Meeting (Seattle, WA) Fullerene Session Co-Organizer	(2001)
The French-US workshop on Nanotechnology (Montreal, Canada) Session Chair	(2000)
The Georgia Tech. Workshop on Nanomaterials (Atlanta, GA) Session Chair	(2000)
American Physical Society March Meeting (Minneapolis, MN) Nano-scale physics Session Chair	(2000)
Engineering Foundation, Symposium on Nano-Composites (Anchorage, Alaska) Co-Organizer	(1999)

5.2.2 External Examiner

(2003) External Examiner Dublin Institute of Technology, Dublin Ireland
(1999-2002) External examiner for Department of Physics, Trinity College Dublin, Ireland
(2000) External Examiner (committee member) for Department of Physics, Tübingen University, Germany.

5.2.3 Referee: Individual

<u>Journals</u>	<u>Funding Agencies</u>
Nature, Applied Physics Letters, Langmuir, NIM Particles and Beams, Physical Review Letters, Physical Review B, Journal Vacuum Science and Technology A and B, Science, J. Chemical Physics Nanotechnology Journal of Nanosciences and Nanotechnology (JNN) Small	DOE ONR NSF NASA AFOSR Army State of Kentucky State of Iowa Government of Sweden Science Ministry SFI (Ireland) DFG (Germany) Government of Switzerland

5.2.4 Referee: Panelist

NASA: Gossamer Program and Nano-initiative
NSF: Nano-initiative and instrumentation grants
(served on 20 panels since 1997: NER, NIRT, MRI, NNI center, Career Award)

SFI: Science Foundation of Ireland
(served on 4 panels since 1997)
National Textile Center: review panel
South Carolina Research Authority: review panel for Lottery Sponsored Centers of Economic Excellence

5.3 University Service

University service includes activities intended to promote the university (Clemson and WFU are included). Also included are activities in which university operations are aided.

5.3.1 University committees - Wake Forest University

Department of Physics, Graduate Committee	(2003 -)
Lower Division Advising	(2004 -)
BME Biomolecular Imaging oversight Board (WFUBMC)	(2004 -)
Faculty Hiring Committee	(2004 – 2005)
Department of Physics Building Committee	(2005 -)
External Advisory Board of the Comprehensive Cancer Center	(2005 -)
Health and Safety Committee of WFU HS taskforce on nanomaterials	(2008 -)
PhD Taskforce on graduate education	(2009 -)
Undergraduate Curriculum Committee	(2009 -2011)
Graduate Committee	(2011 -)

5.3.2 University committees - Clemson University

Department of Physics and Astronomy, Faculty Search Committee	(1998)
Department of Physics and Astronomy, Sigma-Pi-Sigma Advisor	(2000-2002)
Department of Physics and Astronomy, Faculty Search Committee	(2000)
Department of Physics and Astronomy, Colloquium Organizer	(1998-2002)
Department of Physics and Astronomy, Curriculum Committee	(1999-2002)
College of Engineering and Sciences Curriculum Committee:	(2000-2003)
University Undergraduate Curriculum Committee:	(2001-2003)

5.3.3 University committees - Wesleyan University

University Educational Policy Committee	(1991)
University Budgetary Finance Committee	(1990)
University Library Acquisitions Committee	(1989)

5.3.4 University committees - North Carolina State University

Department of Physics President, Society of Physics Students	(1985)
Department of Physics Vice-president, Society of Physics Students	(1984)

5.3.5 University Community Building Activities

The Carroll group has twice sponsored a graduate student poster presentation once at Clemson 2002 and once at Wake Forest 2005.

Between 1997 and 2002 the Carroll group hosted the *Nano-Clemson Meeting*. It is generally attended by 10 Clemson faculty, 5 off campus visitors and speakers with approximately 10 graduate students.

5.4 The Center for Nanotechnology and Molecular Materials



Establishing the Center

The most significant career achievement in service of the University is the establishment of the *Center for Nanotechnology and Molecular Materials at Wake Forest University*. The Center was officially founded and recognized as a research center of Wake Forest University as well as Wake Forest University Health Sciences in 2004. It serves as an infrastructural resource for the WFU research community and is *open access* in operation.



Membership of the center: the center is composed of three user groups – the microscopy users, the cleanroom users, and the testing standards users.

Advisory Board: The user groups each have a representative on the oversight board of the center as well as a representative for graduate students and the University administration.

The facility: The facility is a stand-alone building adjacent to the Wake Forest University campus. This 12,000 sq ft. building contains offices, lab space, core labs and a lecture hall for 50 people. There are two PI labs in the building. Core labs are equipped through private donations, competitively won awards, and indirect return. Total combined assets of the center is ~ \$10M in equivalent new replacement costs. Detailed information on Nanotech Center assets can be found at www.wfu.edu/nanotech or <https://www.wake-nanotech.org>.

The three core labs: 1200 sq ft class 1000 clean room used for device fabrication and lithography
 Device testing lab with Solar, transport, optical metrology testing standards
 Microscopy suite with electron microprobes characterization.

Funding the Center

Upkeep, maintenance and repairs are fundamentally the responsibility of the center, with direct granting, and indirect return used for this purpose. The university has provided some funding to help with operations as well. However, the Center does not have the ability to charge for hourly use at this time.

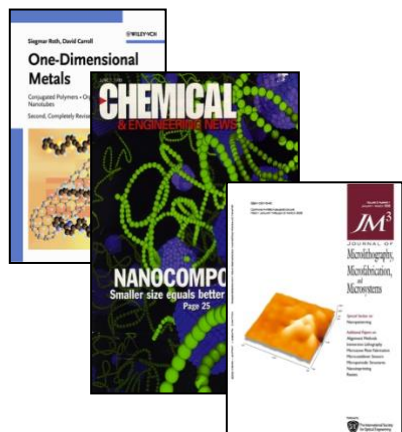
Key Inventory of Center

JEOL 2010F STEM full analytical
 JEOL 1200 EX TEM
 JEOL 6340F SEM
 JEOL 6335F SEM
 JEOL5200 SPM
 RHK UVH STM – with vac
 PHI 570 ESCA/XPS/SIMS system

365nm i line lithography
 -mask aligner
 -3 different deposition systems
 -asher and plasma refinement
 -packaging and wirebonding

AM1.5g class A standard/ICPE
 AM1.5g lateral testing for angle of incidence
 Thermopower, 4 point probe to 10K, peltier
 CIE scaled spectroscopic power analysis
 circuit power analysis

Community Impact of the Center



The Nanotech Center acts as a focal point for nanotechnology and nanosciences activities across the campuses of Wake Forest University. Currently more than 20 faculty have ongoing, funded projects with the Nanotech Center. Further, the Center maintains a guest scientist program, K-12 educational programs, a relationship with WSFC schools for kids, and a list of courses developed for Nano-Sciences at WFU.

Further, a major, long-term goal of the Center is to raise the overall profile of the Science and Engineering activities of Wake Forest University.

Finally, the Nanotech Center is striving to become a nationally recognized center of excellence in nanocomposites, quantum materials and nanomedicine research as determined by our citations, funding, and IP.

The Carroll Group and the Nanotechnology Center in Popular Press; Newsprint, Radio, Television

The Nanotech Center has been featured in numerous print and television outlets. These include: Drug Discovery Magazine, Engineering News, NPR Earth and Sky, Triad Business Journal, Forbes Nanotechnology, Advanced Materials, New Scientist, Triangle Business Journal, Science and Tech. Alert, Science, Winston-Salem Journal, BIOTECH News, The State, C&E News, Engineering News (South Africa), Carolina Business Review NPR, Fox News 9, National Public Radio business news, National Public Radio “Earth and Sky”, National Television Commercials (ESPN), CBS “Eye on America,” the BBC, CNBC, the History Channel, the Discovery Channel, the NY Times, Time Magazine, and CNN.

5.5 Public Service and Outreach



5.5.1 External Boards and Committees

Board Member SciWork (Children’s Museum for Science)	2010 - present
Board member North Carolina School of Science and Mathematics	2010 – present
Organizing Board of Childress Center for Pediatric Trauma (WFU)	2008
Technology Council of the Winston-Salem Chamber of Commerce	2004 – present
External Board for Community Relations, Comprehensive Cancer Center WFU	2006 - present
National Composites Consortium Operating Committee	2004
Materials Research Society Operating Committee	2004

5.5.2 Public Presentations (I stopped tracking these)

2013	2012	2011	2010	2009	2008	2007	2006	2005	2003	2001
Arbor Acers retirement home VF - Nanotextiles	Girl Scouts (local troupe) Hanes Middle School awards lunch	Reagan High WS Kiwana’s School	Hanes Middle Sherwood Elementary School School	Association of Retired Methodist Ministers Humbolt Colloquium	Board of Governors of SciWorks Museum Golfers against Cancer Entrepreneurship Colloquium Wake Forest University Research Council of WFUHS	SciWorks Nanodays Retired Officers Club of the Triad PTEN forum Winston- Salem	Retired Methodist Ministers Golfers Against Cancer Foundation Wachovia Donors Forum	GRCC Health Sciences Winston- Salem Tech Council Research Council of WFUHS	Winston- Salem Chamber of Commerce Technology Council	Greenville Chamber of Commerce SC Department of Commerce

	UNCC REU experience				Winston-Salem Chamber of Commerce	Chamber of Commerce	Era of Hope Foundation			
	VF workshop on the future of apparel				PTEN Forum	Chamber of Commerce Tech council				
					High Point Rotary Club Foundation	Winston- Salem Rotary Club				

5.5.2 Educational Outreach



working to integrate the SciWorks program into the Winston-Salem Forsyth County school system.

2) The Carroll group has established a public speakers series that brings in nanotechnology experts from around the world. Recent speakers have included representatives from the NSF sponsored NNIN, from the Max-Planck Institutes in Germany, from Massey University in New Zealand, and from the business community that deals with nanotech. These talks are held at the Nanotech Center and are open to the public. They are advertised statewide and typically have an attendance of 30 or more.

3) The Carroll group drove the development of a new two year program in Nanotechnology at Forsyth Technical Institute. The curriculum was designed in large part by Dr. Carroll and many of the courses have been taught by Dr. Carroll to help the program get started.



4) The Carroll Group developed a summer camp experience for middle school kids at Hanes Middles School in 2013. The successful camp “Power Up” focused on using real world math skills to build solar power stations and will be taught again this summer due to popular demand. The camp also attracted media attention to WFU from local news channels 14, 12, and 2. Shown left are students from that camp working with solar panels provided by the NanoCenter.

5) The Carroll Group sponsors a Technology Student Association Team at the Hanes Middle Magnet School. This involves weekly contact and mentoring with kids along with attendance and oversight at competitions. This is fully credited as a WFU outreach program.

6) The Carroll Group welcomes one to two visits with girl scout troops per year into the labs to earn science badges. The Group provides a full range of educational activities and explanations of what the girls are doing and certifies their badges for them. In 2013, we hosted two such events: one on rocketry, the other on the chemistry of light.

Note: All activities are done under the auspices of WFU outreach and graduate and undergraduate students of the group fully participate.

5.5.3 Publicity and Outreach

Working together with Media Relations, the Carroll Group has had a significant presence in the national and international media. Shown here are only a few of the examples (we do not track them all).



On the cutting edge:

Community college training for the nanotechnology workforce

October 6, 2006

North Carolina Board of Science and Technology

Corey Whitt and Mike Owens share a deep interest in nanotechnology—but for very different reasons. Whitt's mother has multiple sclerosis, so he's intrigued by the medical applications of the technology that could someday improve his mother's quality of life. Owens is an older-than-average student looking for a career change, and he's attracted to the emerging job opportunities nanotechnology offers.

Yet neither Whitt nor Owens thought he would ever have a chance to follow up on his interest in nanotechnology—the manipulation of atoms and molecules at the nanoscale level, a billionth of a meter. Until recently, no community colleges in North Carolina offered degree programs in the field.

That changed in 2005, when Forsyth Technical Community College announced that it would offer an Associate in Applied Science degree in nanotechnology. It is the first degree of its kind in a North Carolina community college and among only a handful in the nation.

"Nanotech education at the community college level is important to provide the support necessary for further nanotechnology operations in manufacturing and research," says Cynthia Bioteau, the former chief academic officer and vice president of Forsyth Tech. Bioteau was instrumental in the initial development of Forsyth's nanotechnology degree.

Forsyth Tech's nanotechnology program teaches students how to examine and manipulate materials at the atomic level. The program's interdisciplinary curriculum includes coursework in biology, chemistry, physics, math, and manufacturing engineering technology. It teaches students the skills necessary to manufacture products that use nanotechnology, such as plastics, batteries, paints and fabrics. When these students graduate, they may be working in the textiles industry creating softer fabrics, or in a plastics company producing soda bottles with longer shelf lives.



Faculty member Kevin Conley looks on as Corey Whitt, a second-year nanotech student, measures nanoscale features of a silicon surface with an atomic-force microscope.

Image courtesy of Kevin Conley, Forsyth Technical Community College.



Ken Causey, a second-year student in the nanotechnology program at Forsyth Tech, navigates over graphite and gold surfaces with a NanoSurf EasyScan2 Atomic-Force Microscope.

Image courtesy of Kevin Conley, Forsyth Technical Community College.

The program also stresses safety and ethics, which will help ensure that employees working with nanotechnology do so safely and responsibly. It will also prepare some graduates for jobs with regulatory organizations.

"The shelf-life of knowledge in nanotechnology is about 18 months, so our curriculum must continue to develop in response to changes in marketed products, economic trends, and research publications," says Kevin Conley, a professor in Forsyth Tech's nanotechnology program.

By responding quickly to the constantly changing field of nanotechnology, community colleges are proving that they are well-suited to offer degree programs in the field. Community colleges are also relatively affordable, making them ideal for training skilled workers for entry-level positions in North Carolina's modernizing economy. "For a two-year community college degree, success equals jobs," says David Carroll, director of the Center for Nanotechnology and Molecular Materials at Wake Forest University.

Wake Forest played a critical role in the creation of Forsyth Tech's nanotechnology program, investing both money and time into this innovative effort.

Wake Forest continues to play an active role in the day-to-day operation of the program. Some postdoctoral students at the Wake Forest Center for Nanotechnology teach classes at Forsyth Tech. And Carroll, who was invaluable in the development of the degree, still works with several of the instructors on a regular basis, keeping the curriculum in line with current industrial needs.

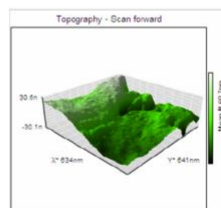
"For the cost of community college in-state tuition, students will gain experience with the most precise measurement instruments available anywhere in the world; develop a foundation in the economics, ethics, and soft skills required to be competitive in the current workplace; and also have access to measurement and fabrication equipment from Wake Forest University," says Conley.

For now, Forsyth Tech students can use the microscopy suite at Wake Forest's Center for Nanotechnology for some of their coursework. But Forsyth Tech is also quickly developing its own nanotechnology facilities. It recently received a \$500,000 grant from the Wachovia Foundation to establish an atomic-force microscopy laboratory right on Forsyth's campus. The devices in the lab have atomic-sized resolution, so students can actually see the atomic structure of a surface, in



Michael Owens, another Forsyth Tech student studying nanotechnology, uses an atomic-force microscope provided through a grant from the Wachovia Foundation.

Image courtesy of Kevin Conley, Forsyth Technical Community College.



Three-dimensional atomic-force microscope image of human skin with low nanometer resolution.

Image courtesy of Kevin Conley, Forsyth Technical Community College.

EarthSkyNews Solar Cells 2007

<http://earthsky.org/human-world/nanotechnology-improves-solar-cell-efficiency>

What is this?

<http://www.amazon.it/David-Carroll-Physicist-Nanotechnology-Nanoengineering/dp/6132844538>

FIPEL-2012

BBC

<http://www.bbc.com/news/science-environment-20553143>

Popular Science

<http://www.popsci.com/science/article/2012-12/new-kind-lighting-could-replace-fluorescents-cfls-and-leds-light-source-future>

Toronto Star

http://www.thestar.com/news/world/2012/12/03/us_scientists_reinvent_the_light_bulb.html

The Business Journal

<http://www.bizjournals.com/triad/news/2012/11/30/wake-forest-nano-scientists-develop.html>

Christian Science Monitor

<http://www.csmonitor.com/Environment/Energy-Voices/2012/1203/New-plastic-lighting-saves-energy.-Goodbye-fluorescent-lights>

PowerFelt 2012

Time

<http://techland.time.com/2012/02/23/new-power-felt-could-charge-your-phone-with-body-heat/>

CNN Video

<http://edition.cnn.com/video/data/2.0/video/world/2012/08/27/coren-people-power.cnn.html>

Discover Magazine

<http://blogs.discovermagazine.com/80beats/2012/02/23/current-fashion-power-your-phone-with-clothes-made-of-thermoelectric-fabric/#.Uz4Ak22a-So>

CINET

<http://www.cnet.com/news/power-felt-could-one-day-run-ipod-from-body-heat/>

Bloomberg BusinessWeek

<http://www.businessweek.com/articles/2012-03-22/david-carroll-turns-fabric-into-an-energy-source>

SolarCells 2007

Science Daily'

<http://www.sciencedaily.com/releases/2007/04/070419140902.htm>

Solar Cells

Journal April 3, 2014

http://www.journalnow.com/news/local/article_1d243ff0-fc9e-11e2-b607-001a4bcf6878.html

NanoWerk 2010

<http://www.nanowerk.com/news/newsid=15692.php>