

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

CANADIAN SOLAR INC.,
Petitioner,

v.

MAXEON SOLAR PTE. LTD.,
Patent Owner.

Case No. IPR2024-01038
U.S. Patent No. 11,251,315

DECLARATION OF DR. MARY K. BOLIN

I, Mary K. Bolin, declare as follows:

1. I am Emeritus Professor at the University of Nebraska, Lincoln Libraries. I have held the following positions: Professor and Catalog and Metadata Librarian, Digital Initiatives and Special Collections Department, University of Nebraska—Lincoln Libraries (2015–2020); Professor and Chair, Discovery and Resource Management and Coordinator of Collection Development, University of Nebraska, Lincoln Libraries (2004–2015); San Jose State University School of Information: Lecturer (2008–present); Head of the Technical Services Department, University of Idaho Library (1993–2003; promoted to Professor in 1999); Head of the Cataloging Department, University of Idaho Library (1986–1993; promoted to Associate Professor and tenured in 1991); and Head of Records Maintenance Section, Cataloging Department, University of Georgia Libraries (1981–1986).

2. Over the course of my work as a librarian, professor, researcher, student research supervisor, and author of numerous scholarly papers and other publications, I have had extensive experience with cataloging records and online library management systems built around Machine-Readable Cataloging (MARC) standards. I also have substantial experience in authenticating printed documents and establishing the date when they were accessible to ordinarily skilled researchers.

3. Attachment A is my full resume.

4. I have been retained by counsel for Maxeon Solar Pte. Ltd. (“Patent Owner”) to evaluate, authenticate, and establish the date of public availability of documents relevant to the above-captioned *Inter Partes* Review proceeding. For my time performing this service, I am being paid my usual hourly fee. I have no financial interest in this action, or affiliation with Patent Owner. My compensation is not dependent upon the outcome of, or my testimony in, this proceeding or any other proceeding, including before the U.S. Patent Office.

A. Documents of Interest

5. The documents that are the subject of this Declaration are the following:

Document 1. Procel, P., Maccaronio, V., Crupi, F., Cocorullo, G., Zanuccoli, M., Magnone, P., & Fiegna, C. (2014). Analysis of the impact of doping levels on performance of back contact-back junction solar cells. *Energy Procedia*, 55, 128-132.

Document 2. Lamers, M. W. P. E., Mewe, A. A., Romijn, I. G., Bende, E. E., Komatsu, Y., Koppes, M., ... & Cesar, I. (2011). Towards 21% efficient N-CZ IBC based on screen printing. *26th EU-PVSEC*.

Document 3. Desa, M. K. M., Sulaiman, M. Y., Sopian, K., Sepeai, S., Azhari, A. W., & Zaidi, S. H. (2014). Optimization of p-type screen printed interdigitated back contact silicon solar cell with aluminum back surface field. *International Journal of Engineering and Technology*, 14(2), 69-80.

B. Methodology

6. I searched for these documents in the OCLC database, Google Scholar, and several subscription databases such as IEEE Xplore and ACM Digital Library. I also searched the library catalogs of institutions such as the University of Nebraska—Lincoln and other large research libraries. My goal was to find a record in one of these databases that contained a date indicating when these documents were available to the public.

7. *Use of MARC Records.* The “Machine Readable Cataloging” standard, also known as “MARC,” is an industry-wide standard method of organizing library catalog information. The Library of Congress first developed MARC in the 1960s. A MARC-compatible library is one that has a catalog consisting of individual MARC records for each of its works. Today, MARC is the primary communication protocol for the transfer and storage of bibliographic metadata in libraries.

8. OCLC is a database of MARC records used by libraries worldwide. When an OCLC-participating institution acquires a work, it creates a MARC record for this work in its computer catalog system, and OCLC automatically supplies the date of creation. The MARC record creation date reflects the date on which (or shortly after) the item was first acquired and cataloged. Once the MARC record is created by a cataloger at an OCLC-participating member institution, it is

instantaneously available to any OCLC-participating members and, therefore, available to the public.

9. A MARC record comprises several fields, each of which contains specific data about the work. Each field is identified by a standardized, unique, three-digit code corresponding to the type of data that follows. For example, a work's title is recorded in field 245, the primary author of the work is recorded in field 100, an item's International Standard Book Number ("ISBN") is recorded in field 020, an item's Library of Congress call number is recorded in field 050, and the publication date is recorded in field 260 or 264 under the subfield "c." If a work is a periodical, then its publication frequency is recorded in field 310, and the publication dates (*e.g.*, the first and last publication) are recorded in field 362, which is also referred to as the enumeration/chronology field. The library that created the record is recorded in field 040 in subfield "a" with a unique library code. When viewing the MARC record online via OCLC's Worldshare Record Manager database, hovering over this code with the mouse reveals the name of the library. I used this method of "mousing over" the library codes in the OCLC database to identify the originating library for all of the MARC records in this Declaration, as well as the "display holdings" command to see a list of libraries that own the item. In the MARC records in the OCLC Worldshare Record Manager database, MARC field 040 contains the OCLC symbols of institutions transcribing, creating, and modifying the record.

10. OCLC was created “to establish, maintain and operate a computerized library network and to promote the evolution of library use, of libraries themselves, and of librarianship, and to provide processes and products for the benefit of library users and libraries, including such objectives as increasing availability of library resources to individual library patrons and reducing the rate of rise of library per-unit costs, all for the fundamental public purpose of furthering ease of access to and use of the ever-expanding body of worldwide scientific, literary and educational knowledge and information.”¹ Among other services, OCLC and its members are responsible for maintaining the WorldCat database (<http://www.worldcat.org/>), which is used by independent and institutional libraries throughout the world. OCLC is the international cooperative to which libraries catalog records and others pay to access MARC records. The MARC records referenced in this Declaration, extracted from the OCLC database, were generated in the ordinary course of business. Further, I personally located and downloaded each of these records associated with the document on which this Declaration focuses.

¹ Third Article, Amended Articles of Incorporation of OCLC Online Computer Library Center, Incorporated (available at <http://www.oclc.org/en-US/membership/councils.html>).

11. OCLC provides its members online access to MARC records through its OCLC Worldshare Record Manager database. When an OCLC member institution acquires a work, it creates a MARC record for this work in its computer catalog system in the ordinary course of its business. MARC records created at the Library of Congress are batch-loaded into the OCLC database through a subscription to MARC Distribution Services daily or weekly. Once the MARC record is created by a cataloger at an OCLC member institution or is tape-loaded from the Library of Congress, it is then made available to any other OCLC members online, and, therefore, made available to the public.

12. When an OCLC member institution creates a new record, OCLC automatically supplies the date of creation for that record. The MARC record creation date reflects the date on which, or shortly after which, the item was first acquired or cataloged.

13. The date of creation for the MARC record appears in the fixed field (008), characters 00 through 05. Field 005 is a 16 digit field that records the date characters `yyyymmdd` including 4 for the year, 2 for the month, and 2 for the day. The date entered on file never changes. These dates are automatically supplied by the OCLC system and cannot be changed by the user. When the MARC record is created in OCLC, it is available throughout the world to other libraries and in WorldCat, the public version of OCLC Connexion. Thus, the date of creation of the

MARC record by a cataloger at an OCLC member institution reflects when the underlying item is accessible to the public.

14. MARC records also include several fields that include subject matter classification information. An overview of MARC record fields is available through the Library of Congress.² For example, 6XX fields are termed “Subject Access Fields.”³ Among these, for example, is the 650 field, which is the “Subject Added Entry – Topical Term” field.⁴ The 650 field is a “[s]ubject added entry in which the entry element is a topical term.” *Id.* The 650 field entries “are assigned to a bibliographic record to provide access according to generally accepted thesaurus-building rules (e.g., *Library of Congress Subject Headings* (LCSH), *Medical Subject Headings* (MeSH)).” *Id.* Thus, a researcher can easily discover material relevant a topic of interest with a search using the terms employed in the MARC Fields 6XX.

15. For Document 1, I performed a search of OCLC (www.oclc.org), which is a large shared database used by libraries around the world to create and exchange cataloging data, using MARC format, which is a universal communications format for that data.

² See <http://www.loc.gov/marc/bibliographic/>.

³ See <http://www.loc.gov/marc/bibliographic/bd6xx.html>.

⁴ See <http://www.loc.gov/marc/bibliographic/bd650.html>.

16. Using the records from OCLC, I determined when each record was created, and which libraries own the items. I then visited the website of the library or libraries that own the items, searched their library catalog, and determined when the items were added to the library's collection.

17. I am familiar with many online catalogs, databases, and search engines. In preparing for this Declaration, I used authoritative information systems such as the above-mentioned WorldCat (<https://www.worldcat.org>), the online catalog of the Library of Congress (<https://catalog.loc.gov>), shared research databases such as ResearchGate and CiteSeerX (formerly known as CiteSeer), the online catalog of a number of large research libraries such as the University of Nebraska—Lincoln, IEEEExplore, and Google Scholar search for records. These records are identified and discussed in this Declaration.

18. The IEEE Xplore⁵ research database is a vital resource for undergraduate and graduate students, researchers, scientists, and the public, offering access to high-quality, peer-reviewed publications. IEEE Xplore serves as a repository for IEEE's ebooks, standards, conference proceedings, technical reports, and journal articles, with content dating back to 1988 and selectively covering materials from 1913 to 1987. The database currently includes over 5.5 million full-

⁵ See <https://ieeexplore.ieee.org/Xplore/home.jsp>.

text documents and is recognized for its rigorous curation and accurate bibliographic records. IEEE Xplore ensures precise reporting of publication dates and event locations in alignment with industry standards for major scholarly and technical journals. Approximately 20,000 new documents are added each month. While abstracts are freely available, full-text access requires a subscription or institutional login.

19. I am familiar with the Internet Archive, a digital library formally certified by the State of California as a public library. Among other services that the Internet Archive makes available to the general public, is the Wayback Machine, an online archive. The Internet Archive's Wayback Machine service archives webpages as of a certain capture date to track changes in the web over time. The Internet Archive has been in operation as a nonprofit library since 1996 and has hosted the Wayback Machine service since its inception in 2001. I consider the Internet Archive's records keeping to be as rigorous and detailed as other formal library records keeping practices such as MARC records and OCLC records.

C. Opinions Regarding Document 1

20. The following are my opinions with respect to the authenticity and public availability of Document 1—Procel, P., Maccaronio, V., Crupi, F., Cocorullo, G., Zanuccoli, M., Magnone, P., & Fiegna, C. (2014). Analysis of the impact of

doping levels on performance of back contact-back junction solar cells. *Energy Procedia*, 55, 128-132.

1. Authentication of Document 1

21. Attachment B is a PDF of the search results page for Document 1 from Elsevier's *ScienceDirect* database, showing a publication date of September 19, 2014.

22. Attachment C is a PDF of Document 1, downloaded from Elsevier's *ScienceDirect* database.

23. Attachment D is a screenshot of the PDF properties of Document 1, showing a creation date of September 19, 2014.

24. Attachment E is a PDF of the MARC record for the conference proceedings that contain Document 1, with a creation date of November 22, 2013. The conference title is *4th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2014) Hertogenbosch, Netherlands 25-27 March, 2014*. Document 1 was also published in Volume 55 of the Elsevier journal *Energy Procedia*.

2. Public Availability of Document 1

25. Based on the facts that Document 1 has a publication date of September 19, 2014 in *ScienceDirect*, with a PDF creation date of September 19, 2014, and that a MARC record for the conference proceedings that contain Document 1 was created

in OCLC on November 22, 2013, it is my opinion that Document 1 was available in libraries in September, 2014.

3. Locating Document 1

26. The *ScienceDirect* database was launched in 1997. (<https://en.wikipedia.org/wiki/ScienceDirect>.) From my experience as an academic librarian, most large academic libraries acquired access to that database by 2008. A skilled researcher could have accessed *ScienceDirect* remotely or in person at any academic or large public library that subscribed to it.

27. For example, Document 1 could have been located by searching the above libraries by some portion of the title (*Impact of Doping Levels on Performance of back Contact-Back Junction Solar Cells*) or by searching for the name of any of the authors, or for significant terms from the conference title (*Proceedings of the 4th International Conference on Crystalline Silicon Photovoltaics* (SiliconPV 2014)).

28. Thus, it is my opinion that someone searching for the title or subject matter of Document 1 would have been able to locate Document 1 in September 2014.

D. Opinions Regarding Document 2

29. The following are my opinions with respect to the authenticity and public availability of Document 2—Lamers, M. W. P. E., Mewe, A. A., Romijn, I.

G., Bende, E. E., Komatsu, Y., Koppes, M., ... & Cesar, I. (2011). Towards 21% efficient N-CZ IBC based on screen printing. *26th EU-PVSEC*.

1. *Authentication of Document 2*

30. Attachment F is a MARC record from OCLC for the conference proceedings that contain Document 2, showing a creation date of February 8, 2012.

31. Attachment G is a PDF of Document 2, downloaded from the ResearchGate scholarly repository.

32. Attachment H is a screenshot of the PDF properties of Document 2, showing a creation date of September 12, 2011.

2. *Public Availability of Document 2*

33. Based on the facts that a MARC record for the conference proceedings that contain Document 2 was created in OCLC on February 8, 2012, and that a PDF of Document 2 is available on ResearchGate with a creation date of September 12, 2011, it is my opinion that Document 2 was available in libraries in September, 2011, and no later than February 2012.

3. *Locating Document 2*

34. From my experience as an academic librarian, most large academic libraries had an online public catalog by 2005, and public Internet access by that time or earlier, a skilled researcher could have accessed Worldcat.org (the public version of OCLC) and sites like ResearchGate, remotely or in person at any academic or large public library.

35. For example, Document 2 could have been located by searching the above libraries by some portion of the title (*Towards 21% efficient N-CZ IBC based on screen printing*) or by searching for the name of any of the authors, or for significant terms from the conference title (26th European Photovoltaic Solar Energy Conference, or by the subject terms, Photovoltaic power systems or Photovoltaic power generation.

36. Thus, it is my opinion that someone searching for the title or subject matter of Document 2 would have been able to locate Document 2 between September 2011 and February 2012.

E. Opinions Regarding Document 3

37. The following are my opinions with respect to the authenticity and public availability of Document 3—Desa, M. K. M., Sulaiman, M. Y., Sopian, K., Sepeai, S., Azhari, A. W., & Zaidi, S. H. (2014). Optimization of p-type screen printed interdigitated back contact silicon solar cell with aluminum back surface field. *International Journal of Engineering and Technology*, 14(2), 69-80.

1. Authentication of Document 3

38. Attachment I is a PDF of Document 3 downloaded from the CiteSeerX repository of Pennsylvania State University.

39. Attachment J is a screenshot of the PDF properties of Document 3, showing a creation date of April 16, 2014.

2. *Public Availability of Document 3*

40. Based on the facts that Document 3 is found in CiteSeerx with a PDF creation date of April 16, 2014, it is my opinion that Document 3 was available in libraries in April, 2014.

3. *Locating Document 3*

41. From my experience as an academic librarian, most large academic libraries had an online public catalog by 2005, and public Internet access by that time or earlier, a skilled researcher could have accessed Worldcat.org (the public version of OCLC) and sites like CiteSeerX, remotely or in person at any academic or large public library.

42. For example, Document 3 could have been located by searching the above libraries by some portion of the title (*Optimization of p-type screen printed interdigitated back contact silicon solar cell with aluminum back surface fields*) or by searching for the name of any of the authors, or for the subject terms Engineering and Technology.

43. Thus, it is my opinion that someone searching for the author, title, or subject matter of Document 3 would have been able to locate Document 3 in April 2014.

* * *

I hereby declare 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 are made with the knowledge that willful false statements and the like are punishable by fine, imprisonment, or both, under Section 1001 of Title 18 of the U.S. Code. I state under penalty of perjury under the laws of the United States of America that the foregoing is true and correct.

Executed this 24th day of March, 2025, in Lincoln, Nebraska.

A handwritten signature in cursive script, appearing to read "Mary K. Bolin", is written over a light gray rectangular background.

Mary K. Bolin

Attachment A

Mary K. Bolin, PhD
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Lincoln, Nebraska 68503
mary@marykbolin.com

Mary K. Bolin, PhD

Professor Emeritus
University Libraries
University of Nebraska—Lincoln
mbolin2@unl.edu

Lecturer,
School of Information
San José State University
mary.bolin@sjsu.edu

EDUCATION

PhD, Educational Studies (Educational Leadership and Higher Education), 2007, University of Nebraska

Dissertation: *A Typology and Discourse Analysis of the Status and Appointments of Librarians at Land Grant Universities* (available at digitalcommons.unl.edu)

MA, English, 1999, University of Idaho

Thesis: *Grace: A Contrastive Analysis of a Biblical Semantic Field* (available at digitalcommons.unl.edu)

MSLS, 1981, University of Kentucky

BA, Linguistics, 1976, University of Nebraska—Lincoln

WORK EXPERIENCE

Center for Digital Research in the Humanities. Fellow, 2019- Emeritus, 2020-

University of Nebraska--Lincoln Libraries: Professor and Catalog and Metadata Librarian, Digital Initiatives and Special Collections, 2015-2020. Emeritus, 2020-

University of Nebraska—Lincoln Libraries: Professor and Chair, Discovery and Resource Management, 2004-2015; Coordinator of Collection Development, 2012-2015

University of Idaho Library: Head, Technical Services Department, 1993-2003. Promoted to Professor in 1999

University of Idaho Library: Head, Cataloging Department, 1986-1993. Promoted to Associate Professor and tenured, 1991

University of Georgia Libraries: Head, Records Maintenance Section, Cataloging Department, 1981-1986

Teaching:

San José State University School of Information:

LIBR 281, Metadata. 2009-

LIBR 248, Introduction to Cataloging and Classification. 2013-

LIBR 202, Information Retrieval. 2008-2013

Associate Coordinator, Gateway PhD program, San Jose State University, 2021-

American Library Association

Cataloging for Non-Catalogers, Online Continuing Education Course, 2017-

Intermediate Cataloging for Non-Catalogers, Online Continuing Education Course, 2018-

Lyrasis

Webinar on BibFrame, taught twice a year, 2020-

Quick and Clean Cataloging, Parts 1, 2, and 3. 2022-

Independent Study in Idaho

Library Science C415, Technical Services for Small Libraries, 2004-2013

Library Science C416, Library Services to Rural Libraries, 2004-2013

Library Science C422, Use of the School Library, 1999-2013

Library Science C425/525, Organization and Management of Small Libraries,
1988-2013

Library Science C427, Library or Media Center Practicum, 1995-2013

Gateway PhD Program (San Jose State University and Queensland University of Technology).
SJSU supervisor for two PhD students, 2015-

Gateway PhD Program (San Jose State University and Manchester Metropolitan University).
Associate Coordinator, 2021-

Consulting

Expert witness for multiple attorneys employed by Wolf, Greenfield & Sacks, P.C.,
Hughes Hubbard & Reed LLP, and other firms. 2017-

Editing

Language and academic editing for [EditSprings](#), a service for international scholars, 2020-

SCHOLARSHIP

Refereed Publications:

(Publications available from digitalcommons.unl.edu)

Bolin, Mary K. (2022). "Academic Libraries and Writing Centers: Collaborations at US Public Research Universities." *School of Information Student Research Journal*, 11(2). Retrieved from <https://scholarworks.sjsu.edu/ischoolsrj/vol11/iss2/2>

Bolin, Mary K. (Forthcoming 2022). *Refocusing Academic Libraries through Learning and Discourse: The Idea of a Library*. Oxford, UK: Chandos/Elsevier.

Bolin, Mary K. (2022). "Metadata, Catalog Systems, Linked Data, and the Evolving ILS." In: Sandra Hirsh (Ed.), *Information Services Today: An Introduction*. 3rd ed. New York: Rowman and Littlefield.

Pytlik Zillig, Brian, and Mary K. Bolin. (Forthcoming) "Visualization of Semantic Primes in Texts from Early Modern English Drama." *Journal of the Japanese Association for the Digital Humanities*.

Wintermute, Harriet E., and Bolin, Mary K. (2018). "Metadata Generators for Backlog Reduction: Metadata Maker Streamlines Cataloging and Facilitates Transition. *Technical Services Quarterly* 35(2) doi: <https://doi.org/10.1080/07317131.2018.1422879>

Bolin, Mary K. (2018). "Metadata, Catalog Systems, Linked Data, and the Evolving ILS." In: Sandra Hirsh (Ed.), *Information Services Today: An Introduction*. 2nd ed. New York: Rowman and Littlefield.

Bolin Mary K. (2017). *The 21-century Academic Library: Global Patterns of Organization and Discourse*. Oxford: Chandos Publishing. (Chandos Information Professional Series)

Bolin, Mary K. (2017). Linguistics and LIS: A Research Agenda." *SLIS Student Research Journal*, 7:1.

Retrieved from <http://scholarworks.sjsu.edu/slissrj/vol7/iss1/2>

Bolin, Mary K. (2014). "Open Access Web Resources for Library Continuing Education and Training." In S. Hines (Ed.), *Revolutionizing the Development of Library and Information Professionals: Planning for the Future* (pp. 107- 124). Hershey, PA: . doi:10.4018/978-1-4666-4675-9.ch008.

Bolin, Mary K. (2014). "The Language of Academic Librarianship: The Discourse of Promotion and Tenure." *Advances in Library Administration and Organization* 32.

Bolin, Mary K. "Librarian Status at US Research Universities: Extending the Typology." *Journal of Academic Librarianship* 34:4 (September 2008)

Bolin, Mary K. "A Typology of Librarian Status at Land Grant Universities." *Journal of Academic Librarianship*, 34: 3 (May 2008)220:230.

Bolin, Mary K. "The Library and the Computer Center: Organizational Patterns at Land Grant Universities." *Journal of Academic Librarianship*, 31:1 (2005)

Eckwright, Gail Z. and Mary K. Bolin. "The Hybrid Librarian: The Affinity of Collection Management with Technical Services and the Organizational Benefits of an Individualized Assignment." *Journal of Academic Librarianship*, 27:6 (2001)452:457.

Bolin, Mary K. "Catalog Design, Catalog Maintenance, Catalog Governance," *Library Collections, Acquisitions, and Technical Services*. 24: (2000)53-63.

Bolin, Mary K. "The Collegial Environment and the Functional Organization," *Journal of Library Administration*. 29:2(1999):49-61.

Bolin, Mary K. "Cataloging Environmental Impact Statements and Related Documents," *Resource Sharing and Library Networks*. 14:1(1999): 21-40.

Bolin, Mary K. "Waiting for the Electrician or Someone like Him: Client-Centered Technical Services" Proceedings of the Association of College and Research Libraries National Conference, Nashville, April 1997.

< http://www.ala.org/Content/ContentGroups/ACRL1/Nashville_1997_Papers/Bolin.htm >

Grants:

Electronic Theses and Dissertations. Seed Grant from University of Idaho Office of Research, 2002. Co PI with Gail Z. Eckwright. \$6500.

Interoperability of Metadata for Thematic Research Collections. Grant to the Center for Digital Research in the Humanities from the Institute of Museum and Library Services 2005-2008. Project Team Member.

http://unlcms.unl.edu/cas/center-for-digital-research-in-the-humanities/projects/pages/iom_files/IOM_Final_Narrative_Report_July_2008.pdf

Other Publications:

Library Philosophy & Practice. Peer-reviewed electronic library science journal. Mary K. Bolin and Gail Z. Eckwright, founders and editors. <http://digitalcommons.unl.edu/libphilprac>

Library Science C415, Technical Services for Small Libraries, through Independent Study in Idaho. 2004.

Library Science C416, Library Services to Rural Libraries, through Independent Study in Idaho. 2004.

Library Science C422, Use of the School Library, through Independent Study in Idaho. Revised 1999.

Library Science C425/525, Organization and Management of Small Libraries through Independent Study in Idaho. Revised 2005.

Library Science C427, Library or Media Center Practicum, Independent Study in Idaho. Revised 1999.

Presentations:

Bolin, Mary K. "BibFrame and the MARC Cataloging Environment: an Introduction." Lyrisis Webinar, June 16, 2020, August 17, 2021.. Recording available <http://lyrisis.adobeconnect.com/paifo9e0dm30/>

Pytlik Zillig, Brian, and Mary K. Bolin. "A Little More than Kin, a Little Less than Kind": the Semantic Field Grace in Early Modern English" Poster Session, Text Encoding Initiative Meeting, Graz, Austria, September 18, 2019

Pytlik Zillig, Brian, and Mary K. Bolin. "Shakespeare and the Enumeration of Semantic Primes." Research Paper Presentation, Text Encoding Initiative Meeting, Tokyo, Japan, September 13, 2018

"Library Philosophy and Practice: Creating and Maintaining an Open-Access E-Journal," Presentation to UNCL meeting (libraries at campuses of the University of Nebraska), Lincoln, Nebraska, March 20, 2008.

Presentation to "Thinking outside the Borders" participants on the open-access electronic journal Library Philosophy and Practice and its role in the international library community. University of Nebraska—Lincoln Libraries, October 24, 2007

Panel discussion on open access electronic journals. GWLA directors' meeting. Linda K. Hall Library, Kansas City, Missouri. April 2007.

"Waiting for the Electrician or Someone Like Him: Client-Centered Technical Services." Association of College and Research Libraries National Conference, Nashville, April 5, 1997.

" 'Some Problems of an Editor': the Idaho Librarian from Manuscript to Published Issue," Joint Annual Conference of the Idaho Library Association and the Washington Library Association, Spokane, Washington, April 6, 1995.

"Automating Idaho's Libraries: a Historical Perspective." Idaho Library Association Annual Conference, Idaho Falls, October 4, 1990.

"Small Library Management." Idaho Library Association Spring Conference, Lewiston, Idaho, May 13, 1989.

"No More 'Good Workers': Excellence and Academic Library Classified Staff." Association of College and Research Libraries 5th Annual Conference, Cincinnati, April 7, 1989.

"Communication to and from Cataloging Departments." Heads of Cataloging Discussion Group, American Library Association Midwinter Meeting, San Antonio, January 1988.

Discussion Leader at the LAMA (Library Administration and Management) Management Exchange. American Library Association Annual Meeting, San Francisco, June 1987.

"Staff Turnover." Heads of Cataloging Discussion Group, American Library Association Midwinter Meeting, Chicago, January 1987.

SELECTED PROFESSIONAL SERVICE

Reviewer. *Resources for College Libraries*. Linguistics bibliography, Spring 2020.

Peer reviewer for ALISE National Conference presentations, Spring 2020.

Peer reviewer for *Journal of Academic Librarianship*, 2012-

Peer reviewer for refereed journal, *Western Nigerian Journal of Medical Sciences* (<http://www.wnjms.org/>), a publication of Ladoke Akintola University of Technology (LAUTECH) Teaching Hospital, 2008-

PhD Reviewer for students from Aligarh Muslim University, India, 2010-

Outside reviewer for numerous library faculty promotion and tenure cases in US universities.

University of Nebraska--Lincoln

Chair, University Libraries Faculty, 2018

Faculty Senate Academic Rights and Responsibilities Committee, 2016- Chair, 2018-19

Faculty Senate – 2004-2008; 2008-2011

Faculty Senate Executive Committee 2004-2008

Academic Planning Committee (APC), 2005-2008; Vice Chair, 2006-2007; Chair, 2007-2008

Aesthetic Review Committee 2006-2007

APC monitor for academic program reviews: Department of Political Science, 2005;
Department of Educational Psychology 2006
Pacific Northwest Library Association:

Editor, *PNLA Quarterly*, December 2002-December 2013

Idaho Library Association:

Editor, *The Idaho Librarian*, September 1990-January 1996

Attachment B



ScienceDirect®

Energy Procedia

Volume 55, 2014, Pages 128-132

Analysis of the Impact of Doping Levels on Performance of back Contact-Back Junction Solar Cells ☆

Paul Procel^a, Vincenzo Maccaronio^a, Felice Crupi^a, Giuseppe Cocorullo^a, Mauro Zanuccoli^b,
Paolo Magnone^b, Claudio Fiegna^b

^a DIMES, University of Calabria, Via P. Bucci c/o Cubo 42/C, I-87036, Rende (CS), Italy

^b ARCES-DEI, University of Bologna, Via Venezia 260, I-47521 Cesena (FC), Italy

Available online 19 September 2014.

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Abstract

In this work, by exploiting two-dimensional (2-D) TCAD numerical simulations, we performed a study of the impact of the doping levels on the main figures of merit in the different regions of a crystalline silicon Back-Contact Back-Junction (BC-BJ) solar cell: the emitter, the Back Surface Field (BSF) and the Front Surface Field (FSF). The study is supported by a dark loss analysis which can highlight the contribution of several recombination mechanisms to the total diode saturation current. The efficiency curve as a function of doping level exhibits a bell-shape with a clearly identifiable optimum value for the three regions. The decrease in efficiency observed at lower doping values is explained in terms of higher contact

recombination for BSF and emitter, and in terms of higher surface recombination for FSF. The efficiency decrease observed at higher doping values is ascribed to the higher surface recombination for FSF and Auger recombination for all cases.

[< Previous](#)[Next >](#)

Keywords

BC-BJ solar cell; TCAD simulation; dark analysis; doping peak



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Energy Procedia 55 (2014) 128 – 132

4th International Conference on Silicon Ph

Analysis of the impact of doping le back contact - back junct

Paul Procel^a, Vincenzo Maccaronio^a, Felice Cru
Zanuccoli^b, Paolo Magnone^b, C

^a*DIMES, University of Calabria, Via P. Bucci c/o Cubo*^b*ARCES-DEI, University of Bologna, Via Venezia 260*

Abstract

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[Numerical simulation of the impact of design parameters on the performance of back-contact back-junction solar cell ↗](#)

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Attachment C

4th International Conference on Silicon Photovoltaics, SiliconPV 2014

Analysis of the impact of doping levels on performance of back contact - back junction solar cells

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Abstract

In this work, by exploiting two-dimensional (2-D) TCAD numerical simulations, we performed a study of the impact of the doping levels on the main figures of merit in the different regions of a crystalline silicon Back-Contact Back-Junction (BC-BJ) solar cell: the emitter, the Back Surface Field (BSF) and the Front Surface Field (FSF). The study is supported by a dark loss analysis which can highlight the contribution of several recombination mechanisms to the total diode saturation current. The efficiency curve as a function of doping level exhibits a bell-shape with a clearly identifiable optimum value for the three regions. The decrease in efficiency observed at lower doping values is explained in terms of higher contact recombination for BSF and emitter, and in terms of higher surface recombination for FSF. The efficiency decrease observed at higher doping values is ascribed to the higher surface recombination for FSF and Auger recombination for all cases.

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Keywords: BC-BJ solar cell; TCAD simulation; dark analysis; doping peak

1. Introduction

Silicon-based Back-Contact Back Junction solar cells (BC-BJ) have been demonstrated particularly promising in order to improve the conversion efficiency because of their architecture with no shadowing areas and simplification of cell interconnection on the rear side. Moreover, efficiencies over 24% have been already reported [1] with the potential to go beyond.

Several works have been developed to study the optimization of BC-BJ in geometry and doping characteristics [2] [3] reporting efficiency trends by changing geometrical parameters. In this work, by exploiting TCAD simulations, we analyse the performance trend of BC-BJ changing the doping peak concentration of emitter, Back

Surface Field (BSF), Front Surface Field (FSF), in terms of recombination losses. In this way, every analysis was developed by performing two simulations: the cell under illumination and under dark conditions to define the recombination losses [4] by extracting Shockley-Read-Hall (SRH), Auger, Surface and contact contributions to the total recombination current and relate them to the efficiency trend.

From this work emerges that, within the range of geometrical and physical parameters considered in our study, the physics of each region is independent from the others and there is a trade-off between two different recombination mechanisms that leads to one optimum intermediate doping peak value for each region.

2. Simulation methodology

Fig.1. shows the sketch of the symmetry element of the simulated solar cells. In this work we considered a floating-zone (FZ-Si) n-type doped 200 μm -thick silicon wafer featuring resistivity 2 $\Omega\cdot\text{cm}$. The doping profiles in BSF, FSF and emitter are Gaussian functions of the spatial coordinate featuring the peak located at the edge of the interface and junction depth of 2 μm for BSF and Emitter and of 1 μm for FSF region.

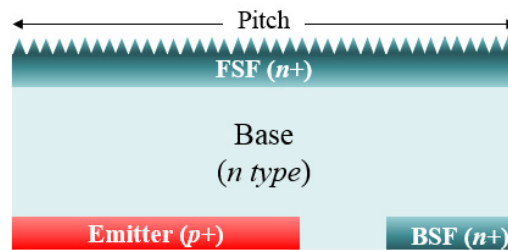


Fig.1. Sketch of the symmetry element of BC-BJ solar cell used in the simulations. Pitch =955 μm , Gap=5 μm

We assumed as simulation parameters the peak doping concentration of the emitter ($C_{\text{em,pk}}$), the BSF ($C_{\text{bsf,pk}}$) and the FSF ($C_{\text{fsf,pk}}$) regions. The front surface is coated by double-layer Anti-Reflective Coating (ARC) composed by 42nm Si_3N_4 and 27nm SiO_2 , texturized by regular upright pyramids featuring a 10 μm base, while the back side is passivated by a 0.1 μm of SiO_2 .

In order to predict realistic values of the figures of merit, the physical models have been calibrated by means of state-of-the-art parameterizations [5]. Fermi-Dirac statistics is adopted to correctly deal with large doping concentrations. The Bandgap narrowing model (BGN) proposed by Schenk is used to account for commonly adopted values of intrinsic carrier density in photovoltaic community ($n_i=9.65\times 10^{-9}\text{ cm}^{-3}$ at $T=300\text{ K}$) [6]. The model proposed by Klaassen in [7] has been adopted in order to model the doping dependent carrier mobility. Auger and radiative recombination models have been parameterized according to Richter *et al* in [8]. Recombination losses due to trap-assisted recombination is modelled by assuming the single-level trap model by Shockley-Read-Hall (SRH); the doping-dependent carrier lifetimes in phosphorus-doped FZ-Si are calculated according to [9]. Surface Recombination Velocity at passivated interfaces has been modelled according to semi empirical models proposed by Altermatt in [10]. The surface velocity at electrodes is set to $1\times 10^6\text{ cm/s}$.

The solar cell has been simulated changing one peak doping concentration in each analysis and assuming the others doping levels constant at optimum values. The study has been performed at $T=298\text{ K}$ under illumination, with a standard AM1.5G spectrum (1000 W/m^2) [11], and in dark conditions to calculate the impact of the recombination losses on the main figures of merit.

3. Results and discussion

In order to understand the impact of doping peak profile on the main figures of merit, we have performed an extensive set of numerical simulations by using the state-of-the-art finite element simulator Sentaurus TCAD [3].

We assumed as simulation parameters the peak concentrations of the emitter doping, of the BSF doping and of the FSF doping. In the following, we discuss separately each analysis.

3.1. Emitter doping analysis

As it can be seen in Fig. 2 (a), remarkable variations of V_{oc} , FF and consequently of conversion efficiency (η) occur with increasing peak doping concentration of the emitter diffusion ($C_{em,pk}$). It is worth noting that the short-circuit current density J_{sc} has a negligible dependence on the peak doping concentration in the emitter region. Indeed, the effects of the doping variation occur in a relatively small region in the rear side of the cell where the carrier photogeneration is the lowest. On the other hand, the FF increases with increasing $C_{em,pk}$ due to a reduction of the emitter sheet resistance. A trade-off between two competitive mechanisms leads to an optimum $C_{em,pk}$ value (at approximately $1.2 \times 10^{19} \text{ cm}^{-3}$) which allows the maximization of the V_{oc} : minority carrier density at contact interface and Auger recombination loss. At first, an increase in doping concentration in emitter region leads to an increase of V_{oc} due to a greater depletion region. However, the decrease in V_{oc} above $C_{em,pk}$ equal to $1.2 \times 10^{19} \text{ cm}^{-3}$ is observed; the degradation of V_{oc} is explained by the trend of the saturation current density calculated under dark conditions illustrated in Fig 2 (b). For relatively low emitter doping concentration peaks, the recombination at contacts is the main component of the total recombination, due to a decrease of minority carriers on emitter region caused by a stronger electrical field on the junction; this explains why the SRH and the Surface Recombination exhibit a negligible dependence on $C_{em,pk}$. However, for peak doping level above $1.2 \times 10^{19} \text{ cm}^{-3}$, Auger recombination becomes stronger and predominant on the total recombination as we expected in the case of doping profiles exhibiting higher peak concentration. Therefore, a trade-off between electrical field intensity in the junction and Auger recombination rate is observed.

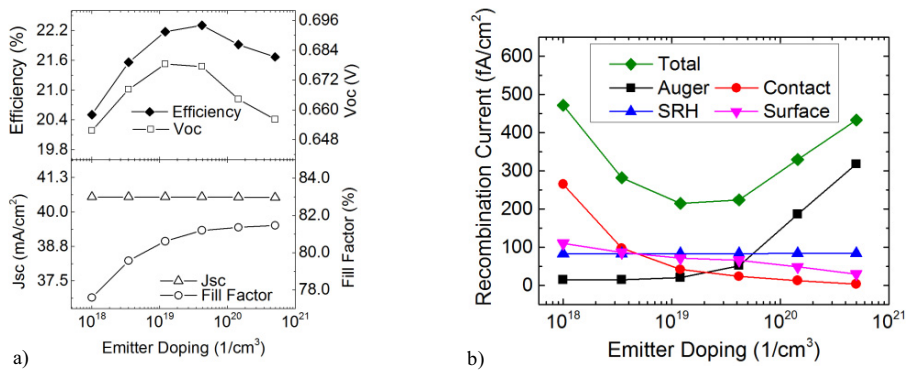


Fig.2. a) Efficiency, open-circuit voltage V_{oc} , short-circuit current density J_{sc} and Fill Factor for Emitter doping $C_{em,pk}$. b) Dark recombination current density components for simulations changing Emitter doping $C_{em,pk}$.

3.2. BSF doping analysis

The change in peak doping concentration on BSF ($C_{bsf,pk}$) has a significant impact on J_{sc} as shown in Fig 3 (a). We observe an increasing trend of J_{sc} with increasing $C_{bsf,pk}$ due to the enhanced effectiveness of the electrical field distribution which prevents minority carrier recombination at the rear contact. In addition, this leads to an increase in V_{oc} . However, as it can be seen in Fig. 3 (b) Auger recombination becomes important for BSF doping peaks above approximately $1.44 \times 10^{20} \text{ cm}^{-3}$. On the contrary, a negligible influence of $C_{bsf,pk}$ on SRH and Surface recombination contributions to the total saturation current density is observed. This is ascribed to the increase in either carrier doping-dependent lifetime and surface recombination velocity at the Si/SiO₂ interface with increasing $C_{bsf,pk}$ which is compensated by a reduction of the amount of the excess of minority carriers thanks to the relatively

stronger electrical field. The trend of the total recombination current is in agreement to those of J_{sc} and V_{oc} ; in conclusion an optimum value of $C_{bsf,pk}$ ($1.44 \times 10^{20} \text{ cm}^{-3}$) can be calculated.

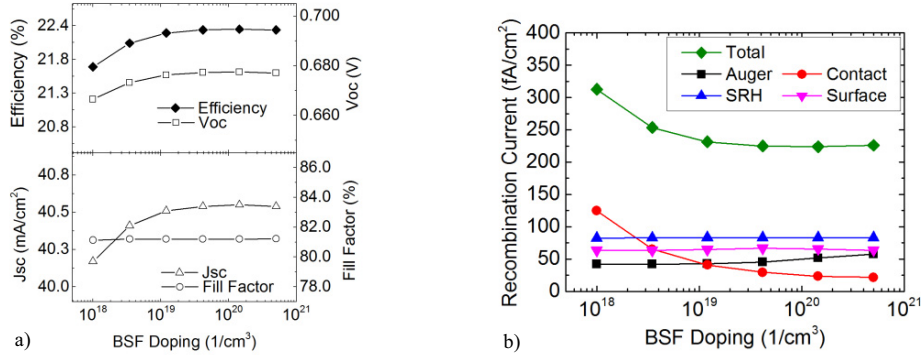


Fig.3. a) Efficiency, open-circuit voltage V_{oc} , short-circuit current density J_{sc} and Fill Factor for BSF doping $C_{bsf,pk}$. b) Dark recombination current density components for simulations changing BSF doping $C_{bsf,pk}$.

3.3. FSF doping analysis

Similarly to the case of the BSF doping analysis, changes in FSF doping peak ($C_{fsf,pk}$) influence markedly the main figures of merit, in particular the J_{sc} , as Fig. 4 (a) shows. According to the dark analysis illustrated in Fig. 4 (b), we observe a decrease in the contribution to the total saturation current density due to the surface recombination at the Si/SiO₂ interface with increasing $C_{fsf,pk}$. Indeed, higher doping peaks lead to relatively more intense electrical field reducing consequently the minority carriers concentration overall in the FSF region. However, for higher $C_{fsf,pk}$ values, the Auger recombination contribution and surface recombination velocity increase enough to become significant.

According to our simulations, the inflection point of the FSF doping is $3.47 \times 10^{18} \text{ cm}^{-3}$. It is worth noting that the increase in SRH and surface recombination current density is marked above $3.47 \times 10^{18} \text{ cm}^{-3}$ thanks to the dependence of lifetime and surface recombination velocity on doping concentration.

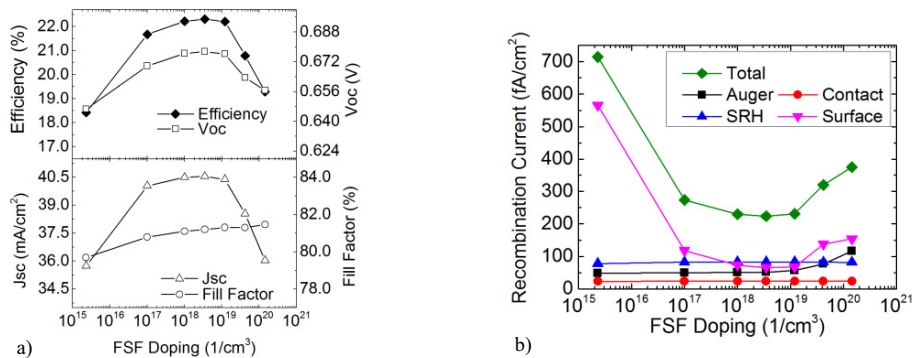


Fig.4. a) Efficiency, open-circuit voltage V_{oc} , short-circuit current density J_{sc} and Fill Factor for FSF doping $C_{fsf,pk}$. b) Dark recombination current density components for simulations changing FSF doping $C_{fsf,pk}$.

4. Conclusions

In this theoretical work we have carried out an extensive study of the impact of BSF, FSF and emitter doping profiles on the efficiency of the solar cell back-contact back-junction. The efficiency curve as a function of doping exhibits a bell shape with a clearly identifiable optimum value for the three doping regions. In our simulated structure, the optimum values of peak doping are: $4.16 \times 10^{19} \text{ cm}^{-3}$ for emitter, $1.44 \times 10^{20} \text{ cm}^{-3}$ for BSF and $3.47 \times 10^{18} \text{ cm}^{-3}$ for FSF. The efficiency decrease observed at lower doping values is explained in terms of higher contact recombination for BSF and emitter, and in terms of higher surface recombination for FSF. The efficiency decrease observed at higher doping values is explained in terms of higher Auger recombination for BSF and emitter, and in terms of higher surface and Auger recombination for FSF. Therefore, the optimum doping peak value is result of the trade-off between surface recombination at silicon interfaces and Auger recombination losses. This means that is expected that the optimum peak doping should change depending on the quality of the passivation at interfaces Si/SiO₂ and Si/Al.

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TOWARDS 21% EFFICIENT N-CZ IBC BASED ON SCREEN PRINTING

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ABSTRACT: Interdigitated Back Contact (IBC) cells have been fabricated at ECN laboratories with a best cell efficiency of 19.1%, using n-type Cz material and a process flow based on all-screen-printed patterning and metallization. Excellent current collection due to an optimized FSF is demonstrated by a J_{sc} value as high as 41.5 mA/cm², corrected for spectral mismatch, and a V_{oc} of 641 mV. The results show high Pseudo Fill Factors (*PFF*) of above 81% but lower Fill Factors (*FF*) of below 72%.

Keywords: back contact, silicon solar cell, high-efficiency

1 INTRODUCTION

Driven by market pressure to increase cell efficiencies and decrease production costs, we have developed a process flow for Interdigitated Back Contact (IBC) cells that is compatible with low-cost industrial processes. The process flow comprises conventional screen-printing steps for patterning and metallization, avoiding more expensive approaches such as lithography [1-3].

High efficiencies (>20%) can be achieved in IBC cells mainly because all current collection contacts are located at the rear, which eliminates the problem of front shading losses. A schematic cross section of the IBC cell can be seen in figure 1. Although optical shading losses are eliminated, recombination losses occur in the regions without emitter as the transport towards the emitter becomes comparable to the local diffusion length. This effect is referred to as electrical shading [4]. To reach the high cell efficiencies, the device structure requires excellent surface passivation at the front and rear sides, as well as patterning of both n- and p-type regions at the rear of the cell and a high bulk lifetime (>1 ms). Narrow and abrupt contact areas will result in reduced resistive and lateral losses. These losses are determined by the minimum feature size, which is limited by the patterning method used. The top-down solution of lithography is able to achieve close to ideal contact regions but the current process is too expensive for high-volume manufacturing. On the bottom-up end, screen-printing is well demonstrated in PV manufacturing and it is therefore important to evaluate the limits in the efficiencies of IBC cells fabricated using this approach.

Since the emitter in IBC cells is located at the rear, an almost ideal surface passivation is required at the front as most charge carriers are created close to that interface. The formation of a high-quality Front Surface Field (FSF) is necessary, which should provide a shielding field effect with no added Auger recombination and can be passivated using a dielectric layer.

In this paper we present the IBC cell made at ECN using tube furnace diffusions, wet-chemical, PECVD and screen-printing (patterning and metallization) process steps alone. The efficiency limits of the fabrication process presented are evaluated by studying the influence of the pitch and emitter fraction, and the effect of unpassivated contacts.

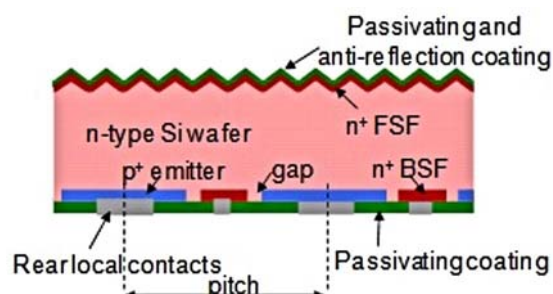


Figure 1: Schematic of an IBC cell, indicating the Front Surface Field (FSF), n⁺-Back Surface Field (BSF), p⁺ - emitter, contacts and passivating layers. The definition of pitch and gap are also included. All contacts are located at the rear.

2 SOLAR CELL AND PROCESS DESCRIPTION

In figure 2 the process flow used to fabricate the IBC cells at ECN is shown. To enable optimal light confinement, the front surface of the cells is textured (random pyramids) using alkaline etching while the rear surface is smoothed which also improves passivation. This wet-chemical process is followed by the FSF diffusion, mainly to reduce the recombination at the front side [5]. After FSF diffusion, the steps include masking, diffusion and patterning of the boron emitter and phosphorus BSF at the rear surface. The emitter and BSF are separated by a non-diffused gap, to avoid shunting. To ensure high efficiencies, front and rear side passivation needs to be excellent. The IBC cells require a rear surface passivation solution for three different surfaces: the highly doped p-type emitter, the highly doped n-type back surface field and the lightly doped n-type base. For this, the full rear side is passivated using a stack of SiO₂/SiN_x:H. The front side is passivated using SiN_x:H coating on top of the FSF. Subsequently, metallization on the BSF and emitter regions is done by screen printing and contacting of both regions is achieved simultaneously by a short high temperature firing step. All patterning and metallization steps were executed using low-cost screen-printing methods. Contacting was achieved by so-called firing-through using an inline belt furnace. The metallization fraction on the rear side was varied between 7.5 and 11.3%, excluding busbars, depending on the pitch.

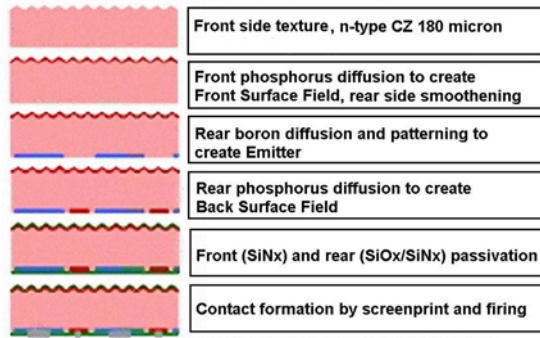


Figure 2: Process flow used for fabricating >19% interdigitated back contact solar cells at ECN.

3 SOLAR CELL OPTIMIZATION

Several aspects of the IBC solar cell can be optimized and in this paper results of various optimizations are presented. These include the FSF, the pitch and the emitter fraction. For the fabrication of the cells 3-4 Ωcm n-type Cz grown Si material was used, for which the bulk lifetime exceeded 1 ms.

3.1 Front surface field optimization

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 $3 \cdot 10^{18} \text{ atoms/cm}^2$ [6-8]. Improved lateral transport by the FSF becomes increasingly important for larger pitches and higher base resistivity. For this, the optimal resistance was found to be 150 Ω/sq for the FSF. These specifications indicate that the FSF profile should be deep, close to $1 \mu\text{m}$. In order to fabricate this by diffusion in an industrial process, a long process time is required which is undesired. For moderate to low bulk resistances and small pitches the additional value of the FSF for lateral transport is of less importance. Under these circumstances, a lightly doped and shallow FSF, with a high resistance in combination with good surface passivation, will give the highest cell output [5]. These specifications allow a short diffusion time in an industrial process. At ECN simulations of the FSF and the related output of the IBC cell were modelled as a function of the surface doping level, depth and the surface recombination velocity at the Si-SiNx interface (S). For the simulations a pitch of 2 mm, emitter fraction of 90%, a bulk lifetime of 1 ms and a Gaussian diffusion profile of the FSF were assumed. In figure 3 and 4 these modelling results are given for the FSF with a depth of 310 and 940 nm. It can be seen that the J_{sc} is optimal for dopants at $3 \cdot 10^{18} \text{ atoms/cm}^3$ for a wide variety of S as it shows that for this doping level the processing is most stable in terms of surface passivation. It was found that J_{sc} decreases for doping levels below $1 \cdot 10^{17} \text{ atoms/cm}^3$. The modelling also showed that for this surface doping level variations in depth of the FSF have not a significant effect on the J_{sc} . The modelling also shows that for a deeper FSF, J_{sc} more steeply declines for higher doping levels. This indicates that in processing a more superficial FSF is more stable and will lead to higher J_{sc} on average.

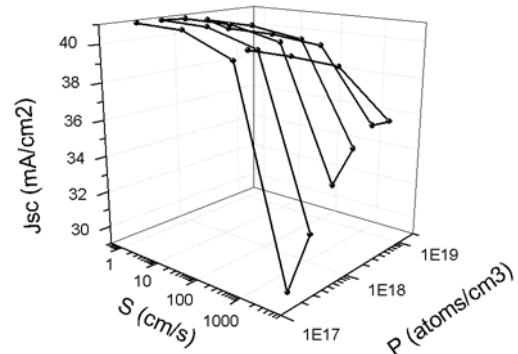


Figure 3: The relationship between the surface doping of the FSF (P), the surface recombination velocity (S) and the J_{sc} for a FSF which is 310 nm deep.

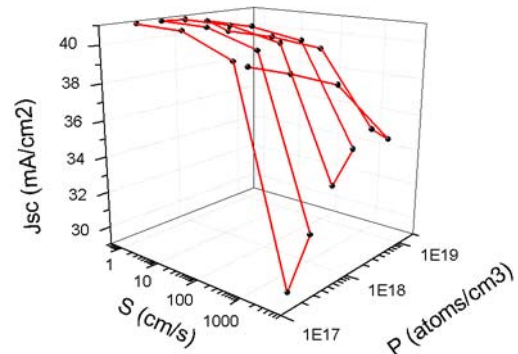


Figure 4: The relationship between the surface doping of the FSF (P), the surface recombination velocity (S) and the J_{sc} for a FSF which is 940 nm deep.

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 $3 \cdot 10^{18} \text{ atoms/cm}^3$ which had a J_{0e} of 44 fA/cm^2 as measured on textured n-type Cz wafers. The sheet resistance was so high that it did not contribute to lateral transport. This FSF should lead to maximal J_{sc} and an optimal IQE.

3.2 Emitter fraction and pitch optimization

As shown in figure 1, the rear side consists of the BSF, the emitter and the gap. The fraction of each region can be varied. The fractions times the pitch give the widths of the different regions. We present here the average of 10 cells per pitch and per emitter fraction. In figures 5 and 6 the effect on the V_{oc} and J_{sc} for two different emitter fractions is given. A clear improvement in J_{sc} is found for a larger emitter fraction. This is due to a reduction in the recombination of the minority carriers as the collection area is increased and the required diffusion distance of the minority carriers is thus reduced. The values for V_{oc} are comparable to values found for other high efficiency screenprinted n-type Cz solar cells [9].

Using light beam induced current (LBIC) measurements, the Internal Quantum Efficiency (IQE) response of the cell at the back of the solar cell can be mapped. In figure 7 the IQE scan of one of the best IBC cells is shown for a wavelength of 976 nm. In figure 8 a line scan of this image is given. This cell had a pitch of

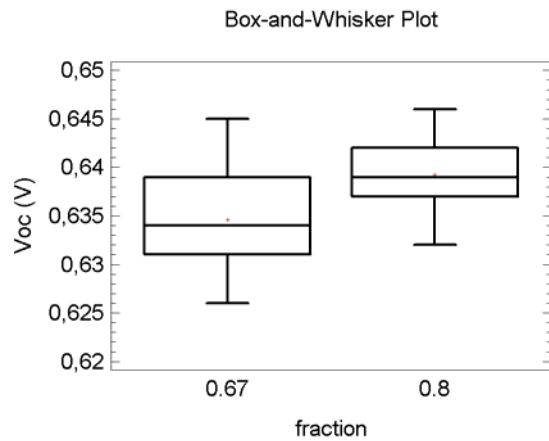


Figure 5: The effect on the V_{oc} for two different emitter fractions.

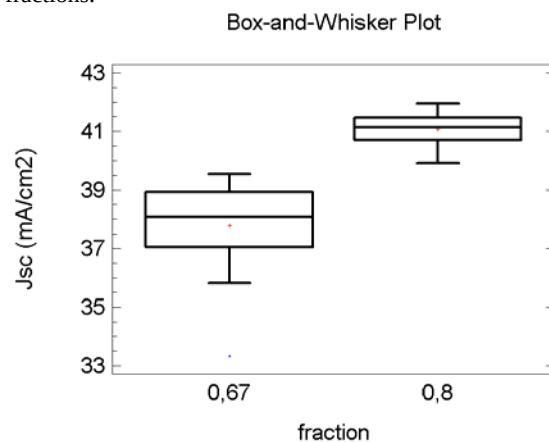


Figure 6: The effect on the J_{sc} for two different emitter fractions.

2 mm, an emitter fraction of 80% and a BSF and gap width of 400 μm . A high IQE of 97% can be seen in the region of the emitter (blue), in the region of the BSF this is 82% (orange/red), with intermediate values in the gap (green). This difference of 15% is due to the electrical shading losses. This is significant lower than was found by others who used a larger BSF and gap region [4,5]. The lower IQE in the BSF region indicates that the passivation needs to be improved. The high doping levels of the BSF, required for good contacting, reduce the passivation of this region [10].

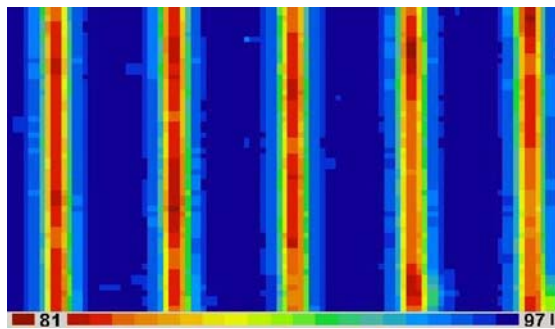


Figure 7: IQE measurement at 976 nm showing the local IQE. Highest IQE is shown in blue (emitter), lowest in red (BSF).

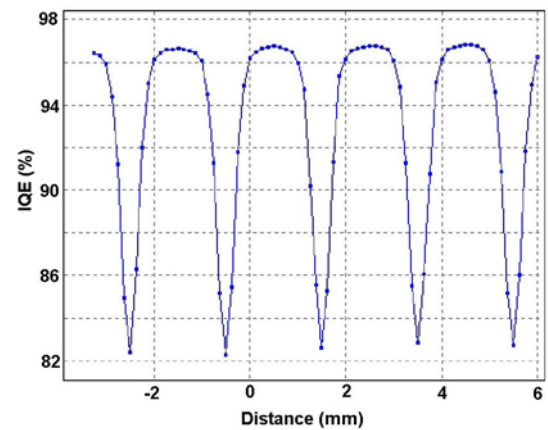


Figure 8: Line Scan of the IQE presented in figure 7. Highest IQE is found for the emitter, lowest for the BSF.

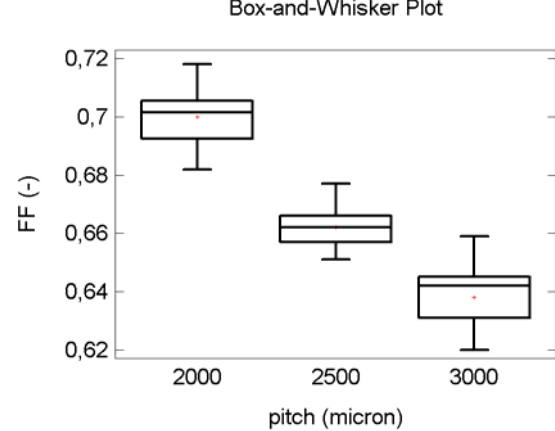


Figure 9: The effect on the FF for three different pitch.

In figure 9 the effect on the FF for three different pitches is given. No effect by the BSF width, gap width and emitter fraction on the FF was observed. A relatively low FF was found with a maximum value of 71.8%, which decreased as contact spacing increased. Combining commonly reported FF values of around 79% with the obtained values for J_{sc} and V_{oc} in this work, would result in cell efficiencies well above 21%. The low FF is currently subject of our research effort.

4 BEST CELL RESULTS

The overall experimental results show that several factors play an important role in obtaining high efficiency. These factors are high quality FSF, high emitter fraction and a small pitch. Figure 10 shows both (a) Internal Quantum Efficiency (IQE) and (b) IV data of our current best IBC cell. A summary of measured parameters corresponding to this best cell with 19.1% efficiency is given in Table 1. For this cell the emitter fraction was 80%, the pitch was 2 mm and the area 13.2 cm^2 .

The IQE results are very good; approaching unity in a broad wavelength range, with characteristic drops in the blue response mainly due to absorption of light in the SiN_x layer, and in the red close to the band gap limit. Excellent current collection is shown by a J_{sc} value as high as $41.5 \pm 1.2 \text{ mA/cm}^2$, as corrected for spectral mismatch. This J_{sc} is close to the maximal current which can be expected from IBC cells [5] and similar to what

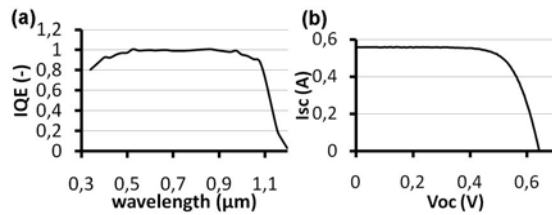


Figure 10: a) IQE, b) IV corresponding to the best IBC cell fabricated.

Table 1. Summary of the best cell parameters which gave an efficiency of 19.1%.

Pitch (mm)	Emitter fraction	J_{sc} (mA/cm ²)	V_{oc} (V)	FF (-)	η (%)
2	0.8	41.5	0.641	0.72	19.1

we obtain on Cz n-MWT cells, when corrected for the front side metallization [9]. This high J_{sc} can be related to the excellent FSF, low electrical shading losses and high-quality surface passivation as discussed before.

5 CONCLUSIONS

The results show that high-efficiency IBC cells, with a top efficiency of 19.1%, have been successfully fabricated using low-cost fabrication techniques such as screen printing for patterning to create the p-n regions and metallization. In general the results show higher efficiencies for larger emitter fraction and smaller pitch, with best results in this study obtained for a large emitter fraction of 80% and a small pitch of 2 mm. The cell was passivated with $\text{SiO}_2+\text{SiN}_x:\text{H}$ for the emitter, BSF and gap, and using an excellent FSF and obtaining low electrical shading losses high J_{sc} values of 41.5 mA/cm² have been achieved. The IQE values are close to unity in a broad wavelength range. Combining commonly reported FF values of around 79% with the obtained values for J_{sc} and V_{oc} in this work would result in cell efficiencies well above 21%. The low FF is currently subject of our research effort..

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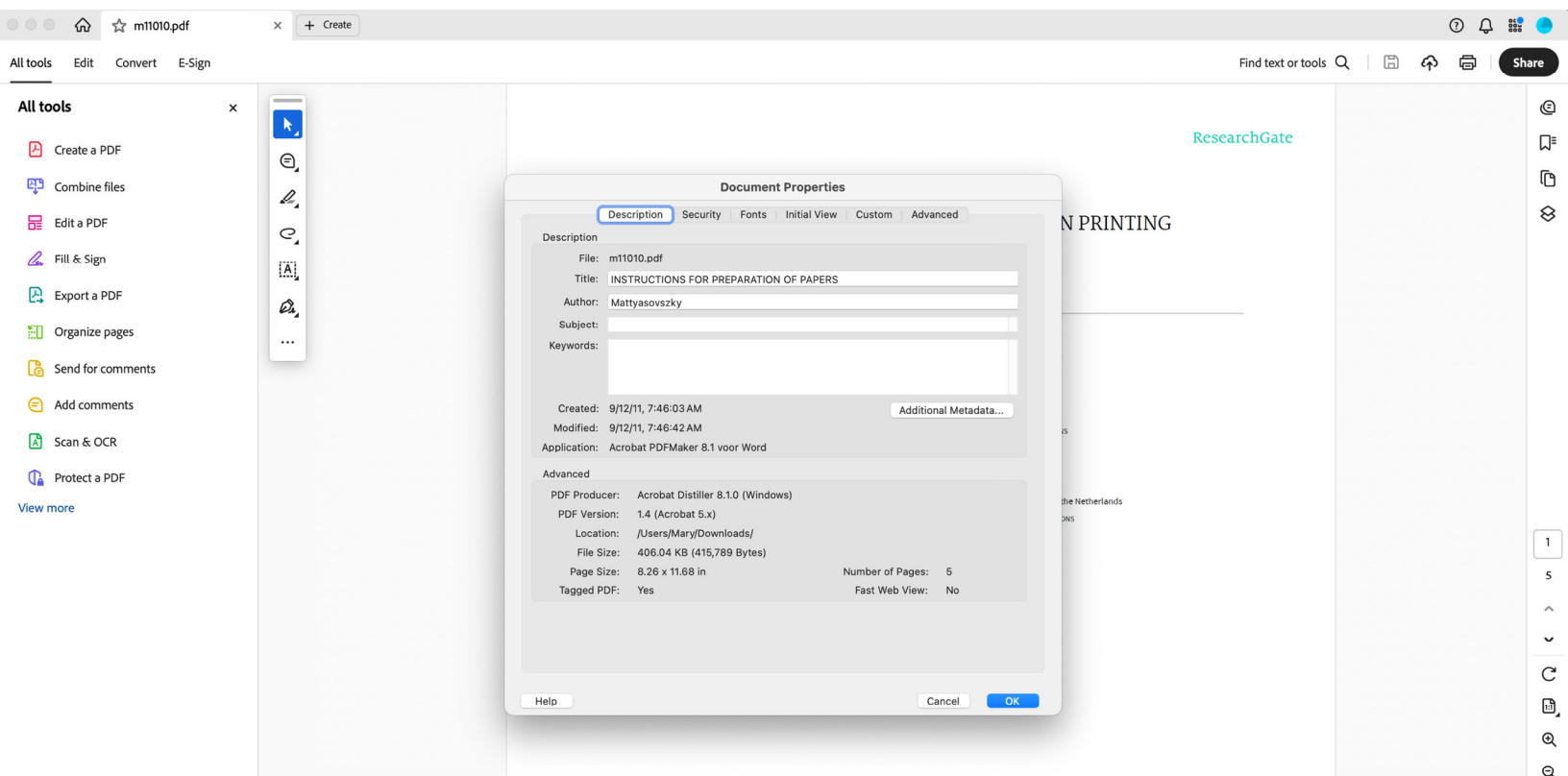
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Attachment H



Attachment I

Optimization of p-type Screen Printed Interdigitated Back Contact Silicon Solar Cell with Aluminum Back Surface Field

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Abstract— Interdigitated Back Contact (IBC) solar cell has been routinely fabricated with efficiencies exceeding 20 %. However, due to the requirements of high- resolution alignment and multiple patterning layers, the IBC manufacturing costs are still high. In contrast, screen printed IBC solar cell is based on inexpensive processes utilizing conventional solar cell equipment. Although the screen printed IBC solar cell is easier to fabricate; however its efficiency is poor. In this paper, the performance constraints on screen printed IBC solar cell based on conventional aluminum metallic diffusion paste were investigated. Two-dimensional modeling was carried out using technology computer aided design (TCAD) tool of the commercial software from SILVACO. Critical process and device parameters impacting IBC solar cell performance including fabrication, configuration and material properties. With suitable starting material, device configuration, and fabrication process, solar cell efficiency as high as 19% has been predicted. Higher efficiency is achievable with boron doping, however, aluminum metallic paste is chosen due to the fabrication simplification which will lead to inexpensive manufacturing.

Index Term— IBC, Interdigitated back contact, Silicon solar cell, Two-dimension solar cell model.

I. INTRODUCTION

It is well known that the efficiency of conventional silicon solar cell is limited by front surface shadow and series resistive losses. Ideally, the front grid contact and the busbar of conventional silicon solar cell must be minimized to reduce shadowing losses. Unfortunately, reducing the contact grid and busbar dimensions increases ohmic resistive losses. Also, the series resistance issues extend to solar modules where many solar cells are interconnected, this decreasing efficiency of module as well. The tabbing size for solar cell interconnection in module fabrication is limited by the busbar size. Larger tabbing width will produce bigger shadowing losses. Thicker tabbing may create stress during cell interconnection, thus affecting yield [1].

The IBC solar cell has all its contacts located at the rear side. Therefore, there is no trade off between shadowing and resistive losses. Shadowing losses are eliminated resulting in higher photocurrent. The finger and busbar dimensions can

now be significantly increased to reduce resistive losses. All these factors contribute to high conversion efficiency as demonstrated by large area IBC modules [2]. Moreover, cell interconnection becomes simpler since the solar cells can be connected in co-planar configuration. Other advantages include higher packing density resulting in a smaller module footprint for the same output in comparison with conventional module. Finally, with its uniform black/dark appearance IBC module is attractive for building integration.

As with other high efficiency structures, a major disadvantage of IBC solar cell is its complicated fabrication process. In IBC solar cell fabrication, a number of process steps and mask levels are needed. For example, separate process and masking steps are used to precisely define physically separate emitter, base, emitter contact and base contact regions. The precise alignment required for the above processes makes the fabrication process slower and expensive. As a result, the IBC solar cell is often fabricated using four to six lithography steps [3]. Lithography is an expensive process and hard to automate. Reducing lithography steps in the fabrication process makes an economic sense [4]. In addition, lithographically-defined emitter and base regions have other disadvantages as well. They require expensive metallization process such as vacuum evaporation or sputtering beam to define the metal contacts.

Recent work has exhibited strong trend towards lithography-free fabrication process of IBC solar cell [5]. These widely different methods include the use of dielectric with laser ablation combined with screen printing [6], diffusion barrier paste [7, 8], diffusion paste [9] and laser scribing [10]. In terms of terminology, these techniques can be broadly categorized under the term “screen printed IBC” as the majority of the methods use screen printing for metal contact. While some of these methods have exhibited reasonable efficiency; others exhibit performance far below than the lithographically defined process. The reduced performance of screen printed IBC solar cell could be attributed to several factors including low lifetime, un-optimized device configuration, low shunt due to leakage, and high series resistances.

The objective of this paper is to investigate the potential of screen printed IBC solar cell by modifying conventional solar

fabrication process based on Aluminum back surface field (BSF). In this paper, effect of doping processes, device configuration, and starting materials will be addressed. To aid this investigation, TCAD tools from SILVACO were employed. TCAD tools were selected due to their ability to simulate two-dimensional (2D) and three-dimensional (3D) configurations. IBC solar cell structure has interdigitated grid of the p- and n-doped regions on the rear surface. This configuration creates both vertical and lateral movement of photo-generated carriers, therefore 2D simulation capability is needed [11-13].

The work presented in this paper has been divided into three parts. The first part is focused on the fabrication process. In fabrication process, the doping profiles of the Front Surface Field (FSF), Emitter, and Base doping were investigated. The second part is focused on optimization of the geometrical configuration of the screen printed IBC solar cell. In this part, performance variation as a function of emitter fraction, base fraction, and emitter-based separation were investigated. The third part examined material characteristics including minority carrier lifetime, bulk doping, and wafer thickness.

II. DEVICE MODEL AND PARAMETERS

A. Base Unit Cell Structure and Parameters

The TCAD tools consist of two separate programs; Athena and Atlas. Athena allows simulation of 2D and 3D configurations. Relevant semiconductor fabrication processes such as diffusion, ion implantation and etching can be modeled. Atlas, on the other hand, is a device simulator. It allows simulation of the electrical, optical and thermal behavior of semiconductor devices [14]. Results in Atlas can be represented as graphical plots such as photogeneration, doping profile, IV response, and electric potentials. The overview of simulation process is described in Fig. 1.

Although there are many papers covering simulation of IBC solar cell, many of the models do not represent low cost device. Most of the simulation models use boron dopants for base region and back surface field (BSF) formation. Boron provides a superior p⁺ region and BSF, however, it does not conform with the conventional screen-printed IBC. The boron diffusion process, not only requires very high temperature, its application needs masking layers as well, therefore making fabrication process more challenging and difficult. The model presented here uses Aluminum (Al) or a mixture of Silver and Aluminum (Ag/Al) pastes to provide p⁺ dopants and create the BSF.

IBC model presented here is represents extension of the work of Baraona [11], Hacke [7] and Meier [15]. A common feature of their IBC solar cells was diffusion of metallic contact. Diffusion of metallic contact is an attractive concept because of the simplification it brings to the manufacturing process; it is also a standard process in conventional solar cell manufacturing. In this concept, ohmic contact as well as dopants are introduced together and are self-aligned. Therefore, the fabrication steps are reduced resulting in elimination of the alignment process. At present, only Aluminum is used widely as the self-doping base contact. The

use of Aluminum as diffusion metallic paste is well-established in literature [13, 16-19].

During the IBC solar cell simulation, higher density meshes were placed in high recombination areas including front surface, contacts regions, and the rear surface. This ensures rapid simulation process without compromising performance accuracy. The starting material used was p-type with substrate resistivity of 2 $\Omega\cdot\text{cm}$ and a thickness of 200 μm ; unit size length was 3000 μm . A p-type wafer was chosen since it is readily available and inexpensive. P-type wafers are also widely used in the Si solar cell industry, which can lead to rapid transition to industrial manufacturing [20]. Same methodology can be applied to n-type wafers, and will be reported in the future.

The modeled screen-printed IBC is schematically described in Fig. 2. The emitter or n⁺ regions and front surface field (FSF) layer (floating junction) were created by phosphorous implantation. The uses of floating junction instead of FSF simplify the fabrication process since it can be formed simultaneously with emitter in phosphorous Trichloride (POCl₃) furnace. Floating emitter helps passivate the front surface and reduces carriers recombination by preventing minority carriers to flow to the surface [21].

The emitter metal contact was Ag. The contact dimension was chosen to be 1-mm wide, although finer contact dimension is desirable in order to reduce carrier recombination near the contact region. For the base region, Al was selected for the contact as well as dopant source. Al provides p⁺ dopants that were self-aligned to the base contact width. The use of Al enables an evaluation of the performance of a low-cost and simplified IBC structure.

Isolation between emitter and base region can be achieved by many methods including laser ablation or etching. Alternatively, isolation can be achieved with the help of diffusion barrier prior to emitter diffusion. In an actual device, the choice of isolation will has a strong influence on the performance because it determines the shunt resistance. In this IBC model, isolation between emitter and base regions was assumed perfect. Other simplifications made in the model include finite ohmic contact resistance and planar front surface (no texturing).

SiN_x layer was deposited as passivation and anti-reflective coating. The front surface recombination velocity (FSRV) of SiN_x layer and oxide passivated surface can reach as low as 14 cm s^{-1} [22]. In this work, a more realistic value of 500 cm s^{-1} was chosen for FSRV. For back surface recombination velocity (BSRV), the value was set slightly higher at 1000 cm s^{-1} due to the high recombination in screen printed contact region [23]. Another distinct feature incorporated in the IBC structure was symmetrical design as shown in Fig. 3 (left). The solar cell parameters used for simulation have been listed in Table 1.

For ATLAS simulation, Boltzmann and Fermi-Dirac carrier statistic models were employed. For mobility, the concentration dependent model based on simple power law temperature dependence was applied. Shockley Read Hall (SRH) concentration dependent was used for recombination

model [14]. An AM1.5 light was used to generate photo response of the solar cell.

III. RESULTS AND DISCUSSION

A. Doping Concentration of Front Surface Field, Base and Emitter

The objective of these simulations is examine how the doping profile influences the performance of screen printed IBC. Figure 5 plots the response of the open circuit voltage (V_{oc}), current density (J_{sc}), Efficiency and Fill Factor as a function of the doping concentration of the emitter, base and FSF regions. At each point the doping concentration corresponding to other three regions are maintained the same. Figure 5 (a) plots the V_{oc} against the doping concentration. It is observed that V_{oc} increases until it levels off after the doping concentration in the emitter reaches $1 \times 10^{19} \text{cm}^{-3}$. Sufficient doping of emitter is required to form built up potential in junction region. The V_{oc} is however not affected by changes in concentrations of the base and FSF.

In contrast, current density, J_{sc} , increases significantly with the increase in the front surface field doping as seen in Fig. 5 (b). The significant effect of the front surface field is due to the high number of photogenerated carriers generated near the front surface as seen in Fig. 4. The electric potential created by the FSF layer repels minority carriers, which reduces the front surface recombination velocity [13]. The J_{sc} also increases with increase in the base doping concentration. The base doping creates a BSF that reduces the carrier recombination at the rear side [24], which is beneficial especially for a back contact structure in which all the photo-generated carriers created at the front surface are collected at the rear side.

From Fig. 5 (c), it can be inferred that the cell efficiency was dominated by the FSF doping. The efficiency increase is also appreciable with base doping; this effect is least impacted by emitter doping. Therefore, achieving good FSF doping is essential for superior performance of the IBC solar cell. Figure 5 (d) shows that the fill factor of the solar cell is barely influenced by doping concentration of the FSF and base doping. There is only slight increase in fill factor due to the surface field created on the front surface, BSF, and emitter region. The fill factor of the cell is related to the bulk doping and contact resistance. Since bulk doping and contact resistance are fixed; no appreciable variation in fill factor was observed.

Doping process also enhances conductivity of a semiconductor. This is requirement for formation of ohmic contacts to emitter and base regions. Doping concentration of $1 \times 10^{19} \text{cm}^{-3}$ corresponding to $0.002 \Omega/\text{square/}$ or lower are necessary for ohmic contacts. However, overdoping increases recombination, creates a dead layer reducing the cell response to short wave photons [25].

B. Geometrical Design of Cell

1) Pitch Dimension

The pitch of the cell is the size from emitter to emitter contacts or the equidistance between similar patterns that comprise the cell (Fig. 6). A smaller pitch results in finer

pattern. The pitch size also determines the methods used for fabrication of the solar cell. Finer pitch requires a photolithography-based pattern resolution, whereas larger pitch allows more versatile, inexpensive equipment such as screen printing. In this paper, pitch dimension was varies in order to examine the effect on the solar cell output performance.

Fig. 7 plots the efficiency of the IBC solar cell with increasing pitch dimension. The pitch size effect can be described in terms of electrical shading [26]. If minority carriers are generated above the base region, the carriers have to travel in vertical and lateral dimension to be collected at the nearest emitter region. Increasing the pitch size increases the lateral dimension of the carrier. As a result the minority carriers have to travel a longer distance before being collected. Some of these carriers might recombine due to longer traversing distance before being collected. This will reduce the carrier collection, therefore reducing the efficiency of the devices as the pitch is increased.

2) Emitter Fraction

The emitter fraction is the percentage of the emitter region over the base plus the compensation regions on the backside. The emitter of the solar cell is where the photogenerated carriers are separated. In theory, a larger emitter area results in larger junction area, and thus, more photogenerated current can be collected. In this structure, we vary the emitter region and fix the base region. Higher emitter fraction and smaller pitch size reduce the effect of electrical shading. Fig. 8 plots efficiency with respect to emitter fraction variation. As expected, a larger emitter fraction results in higher efficiency of the IBC solar cell

C. Material Properties

1) Minority Carrier Lifetime

Minority carrier lifetime is the duration within which a photogenerated carrier will recombine. The lifetime τ of minority carrier is equal to the number of generated carrier Δn over the recombination rate, R (please see Eq. 1). The bulk lifetime of wafer τ_{bulk} is the sum of the radiation lifetime τ_{rad} , auger lifetime τ_{auger} and SRH lifetime τ_{srh} as described in Eq. 2. For indirect bandgap such as silicon, the influence of τ_{auger} and τ_{srh} is more significant. The τ_{auger} increases as doping or impurity introduces to silicon material are reduced while τ_{srh} is related to the defect in the crystal structure of the material. The lifetime is also an indication of diffusion length L_n , of minority carrier according to Eq. 3 where D is diffusivity of silicon material. L_n determines how far the minority carrier travels before they recombine.

$$\tau = \frac{\Delta n}{R} \quad (1)$$

$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{auger}} + \frac{1}{\tau_{srh}} \quad (2)$$

$$L_n = \sqrt{D\tau} \quad (3)$$

Placing all the contacts to the rear side not only changes the physical configuration of the device but also the way it functions. In IBC solar cell, the junction or emitter region is located at the rear side in an interdigitated arrangement with the base region. Therefore, photogenerated carriers have to travel through the bulk before they are collected by the emitter and base region contacts. The photogenerated carriers have a greater chance of recombining in IBC solar structure. The importance of good passivation [27], [28] and FSF [13, 29] to reduce recombination have been discussed previously.

Simulation results in Fig. 9 show that for poor minority carrier lifetimes, the majority of the photogenerated electron-hole pairs recombine before reaching the contacts. As lifetime increases, the V_{OC} , J_{SC} , and efficiency also increase accordingly with greater gains in the current density. However the gains are less substantial as the lifetime increases to more than $1e^{-4}$ s, which suggests that as long as the wafer has sufficient minority carrier lifetime for electron-hole pairs to reach the rear side contacts, the efficiency of the IBC solar cell will remain satisfactory.

2) Wafer Thickness

The cost of Si material is significant in solar cell manufacturing. In industrial Si solar cells, Si thickness is currently in the range 150 μm to 200 μm based on existing wafering capabilities [30]. Innovative cleaving techniques capable of producing thickness in the range of 10 μm to 50 μm exist, but such thin wafers require special handling that cannot be obtained with conventional screen printing methods [31].

To obtain an insight on how the thickness of the wafer influences the performance of screen-printed IBC solar cell, screen-printed IBC with varying thicknesses is evaluated. Two sets of simulations were performed. The first set of simulations was for high carrier minority lifetime wafer and the second set for low minority carrier lifetime wafer. The effect of thickness on high and low quality substrates is examined. Using diffusivity of silicon as $27\text{cm}^2\text{s}^{-1}$, lifetime of 1 ms and 10 μs corresponded to diffusion length of 164 μm and 1643 μm (Eq. 3) for low and high lifetime wafers.

For wafers of lifetime 1 ms, the highest efficiency is 15 %, as shown in Fig. 10, corresponding to 250 and 300- μm thicknesses. With decreasing thickness, the efficiency is slightly reduced due to the presence of less Si substrate to capture all the incident photons. Therefore, some of the light going into the Si is not absorbed because of the less bulk region. Higher wavelength of light, such as photons near the infrared region, confirm this tendency. The effect can be reduced by employing good anti-reflective coating and light trapping such as texturing.

For the low lifetime wafers, the highest efficiency cell is 10.55 % corresponding to a thickness of 20 μm . As thickness increases to 50 μm or higher, there is significant drop in efficiency even though this thickness is within the diffusion length of minority carriers. The drop in efficiency is due to the shorter diffusion length of the photogenerated carriers, which leads to recombination of most of the carriers before they can

be collected at the rear side. In general, diffusion length of three times the wafer thickness is required for sufficient carrier collection.

For screen printing applications, the current wafer thickness in the market is adequate as long as the carrier lifetime is reasonable. A wafer with thickness below 200 μm is fragile and susceptible to cracking during screen printing and handling processes.

3) Wafer Bulk Doping

Another important wafer characteristic is its bulk doping level. Impurities such as P, B, or arsenic are added to reduce the resistivity and defined the type of the semiconductor. However, increased impurity level degrades the electronic properties of silicon. Increasing dopant concentrations reduce minority carrier lifetime because of the increase in SRH and Auger recombination [25]. Figure 11 illustrates that the poorest performance of a IBC solar cell is from a low resistivity substrate exhibiting an efficiency of less than 1 %. As resistivity increases, gain in efficiency is observed. Considering the data in Fig. 11, an optimum efficiency can be achieved for substrate resistivity of about $5\ \Omega\cdot\text{cm}$. Within this resistivity, edge recombination can be suppressed [32]. For higher resistivity substrate, the efficiency decreases because of lower fill factor attributed to higher bulk resistivity.

4) Aluminum and Boron dopants.

With an optimized doping process, device configuration, and wafer material properties, an efficiency of 19.1 % screen-printed IBC solar cell is achievable. Considering the planar front surface, an efficiency gain of more than 20% would be expected if the front surface was textured. Interestingly, when Boron was used to replace Aluminum dopants for the base contact, a higher efficiency was obtained as seen in Fig. 12.

To investigate this effect further, profiles of Aluminum and Boron concentration were examined as shown in Fig. 13. The Aluminum doping profile has very shallow high concentration dopant region at around 0.5 μm thick. As depth increases, there was very steep decline of aluminum concentration with depth. On the other hand boron profile exhibits much deeper high concentration region of about 1.2 μm . Boron doping profile exhibits less steeper decline in concentration with depth resulting in deeper diffusion profile. Part of the reason of shallower aluminum doping profile is the larger particle size of Aluminum compared to Boron. Boron with smaller particle size can diffuse deeper with silicon.

Fig. 14 plots the surface potential of Boron and Aluminum dopants. It can be seen that although Aluminum produces higher surface potential, the field is very shallow and concentrated near the surface region. Boron dopant in the other hand created much deeper electric potential. This results in more effective BSF than Aluminum hence higher efficiency device. The superior performance of Boron than Aluminum is well-established in literature [16].

Nevertheless, the use of Aluminum or Ag/Al provides a simpler fabrication of screen printed IBC solar cell. A recent research indicate that the quality of the Aluminum BSF can be

enhanced by mixing with Boron [33]. In the study Boron was added to Aluminum metal paste to provide better BSF in conventional silicon solar cell. Therefore, this technique can be applied to screen printed IBC solar cell as well.

IV. CONCLUSION

In this paper, a 2D model of screen-printed IBC solar cell has been investigated. The model was based on Aluminum metallic paste diffusion. A detailed analysis based on doping concentration, device configuration and wafer material characteristics was carried out. Achieving an optimal doping profile of FSF, emitter, and base doping is critical to highest performance. Regarding the pattern configuration, the limit will depend on screen printing accuracy since fine pitch and higher emitter fraction are desirable for better IBC performance. Regarding the starting material, high minority carrier lifetime is perhaps the most critical factor dictating the performance of IBC. With optimized solar cell parameters, an efficiency of 19% can be achieved for an inexpensive, screen printing-based solar cell. Efficiency is, in part, limited by the metallurgy of Aluminum when diffused with Si. Aluminum and Boron co-diffusion could further enhance efficiency; further research is required. In summary, Aluminum provides simplified fabrication process exhibiting performance good enough for industrial manufacturing.

ACKNOWLEDGEMENT

The authors would like to thank Solar Energy Research Institute staff for access to SILVACO software.

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FIGURES

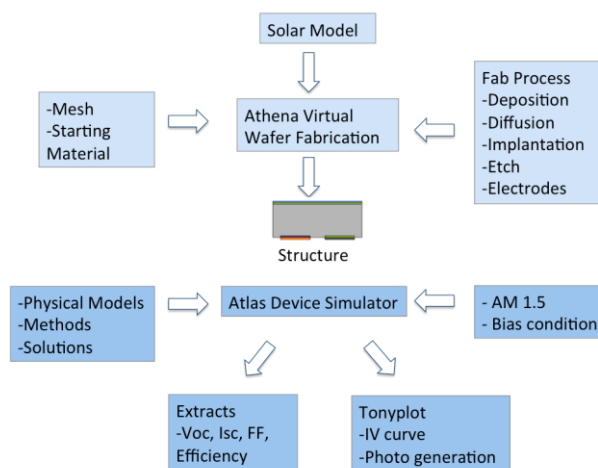


Fig. 1. Modeling IBC solar cell structure process in SILVACO TCAD tools.

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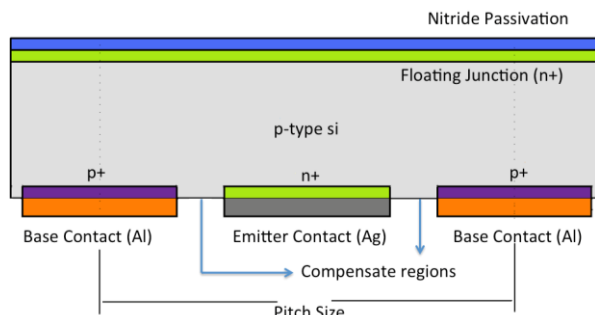


Fig. 2. Cross section of screen printed IBC. The base region was doped with Aluminum dopants to simulate screen printing. Aluminum produces the p+ dopants for the back surface field (BSF) and also acts as the base contact.

IMAGE SIZE: 88 mm/181 mm
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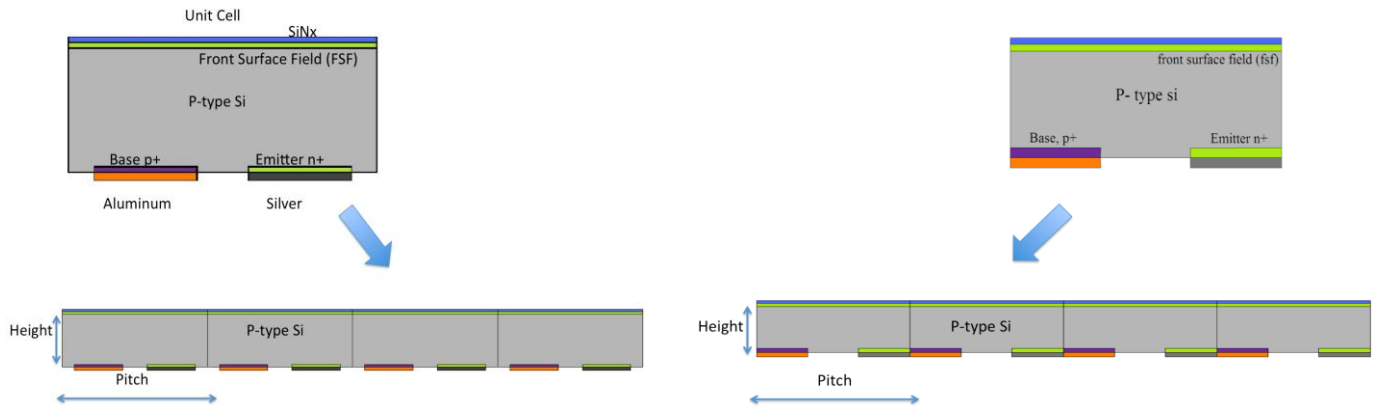


Fig. 3. Cross section of unit cells used in the simulation. The unit cell mapped the entire structure by repeating the symmetrical geometry. Symmetrical structure is shown on the left while unsymmetrical structure is shown on the right. Unsymmetrical structure resulted in inaccuracy in the representation of the whole structure.

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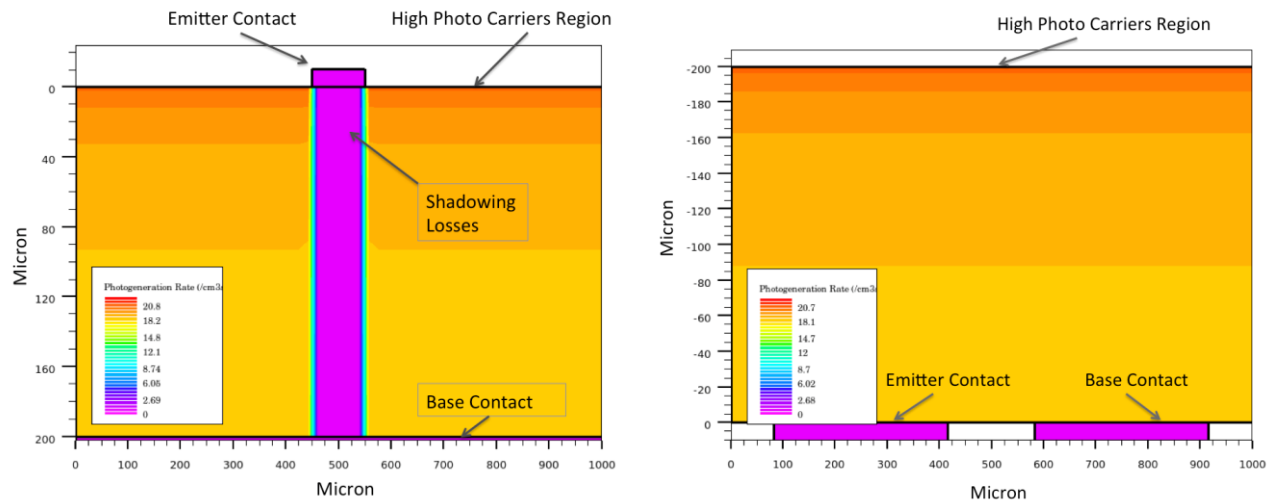


Fig. 4. Photogenerated carriers density in an IBC and conventional screen printed (left) solar cell during illumination. Highest fractions of photogenerated carriers are located near the front surface. Shadowing losses can be observed in SP conventional solar cell.

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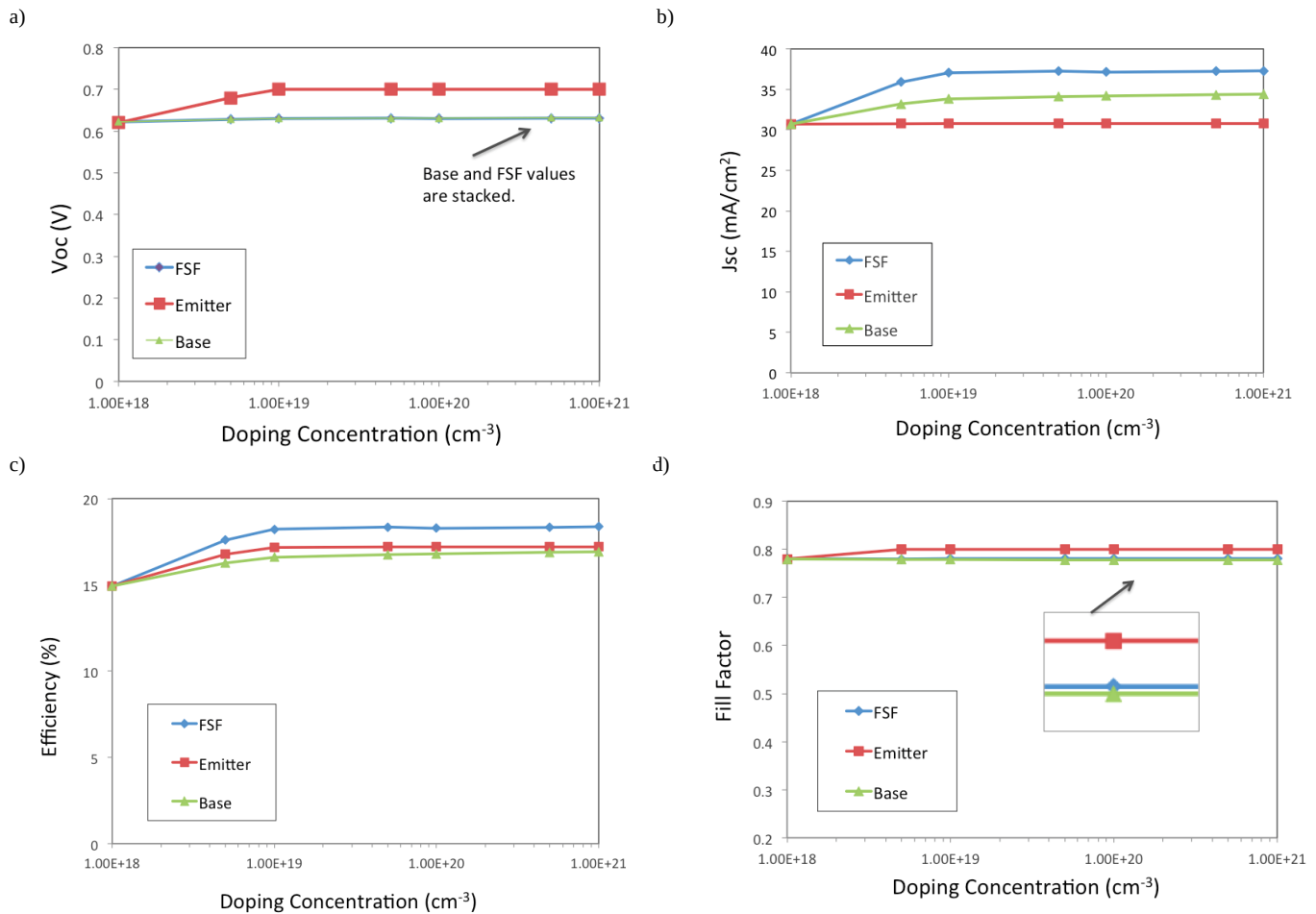


Fig. 5. Variation of (a) Voc, (b) Jsc, (c) Efficiency and (d) Fill factor of Front Surface Field, Base and Emitter doping as a function of the doping concentration.

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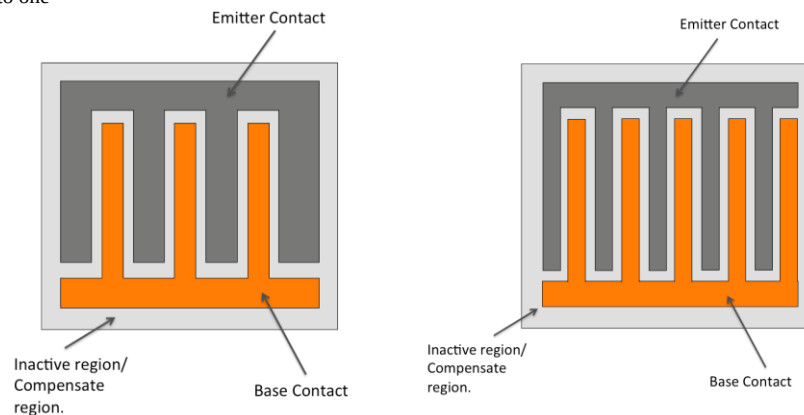


Fig. 6. Rear view of IBC solar cell. Low pitch (left) and high pitch (right) structures of the IBC solar cells.

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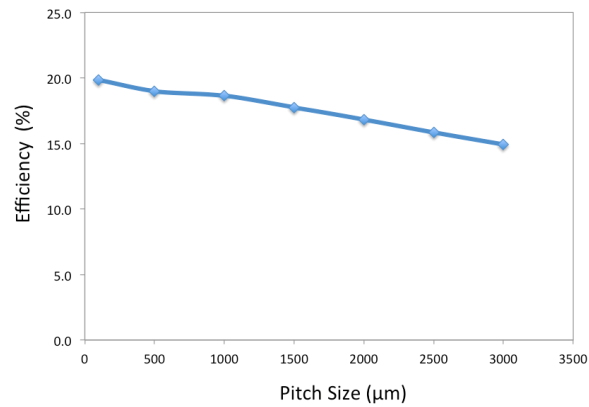


Fig. 7. Variation of efficiency of IBC solar cell for different pitch dimensions. As the pitch size is reduced, the probability of carrier collection increases resulting in higher efficiency cell.

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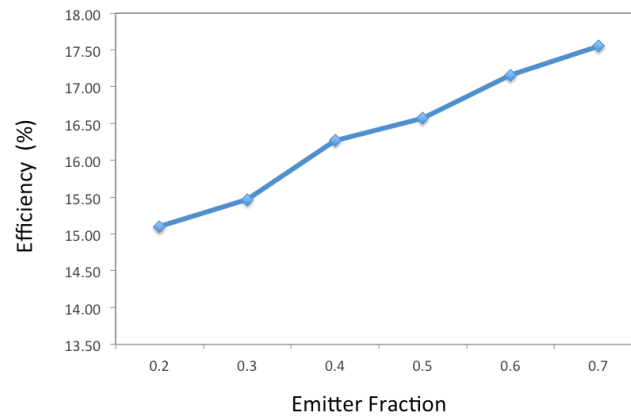


Fig. 8. Variation of efficiency of IBC solar cell for different emitter fractions. Bigger emitter fraction results in higher efficiency IBC solar cell.

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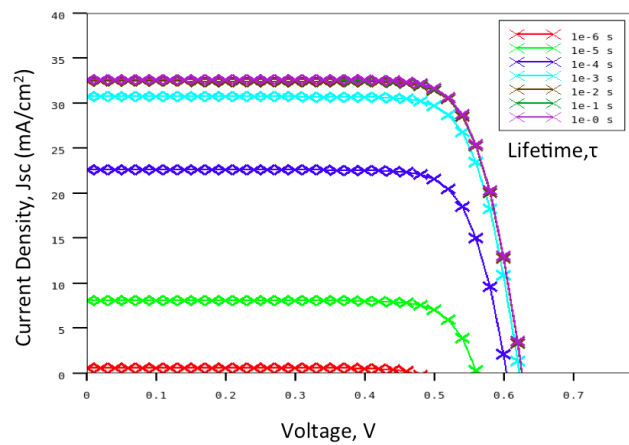


Fig.9. LIV response of IBC solar cells as function of minority carrier lifetime. As the lifetime increases more photo generated carriers have higher chances to be collected.

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FIGURE AXIS LABEL: Voltage (V)

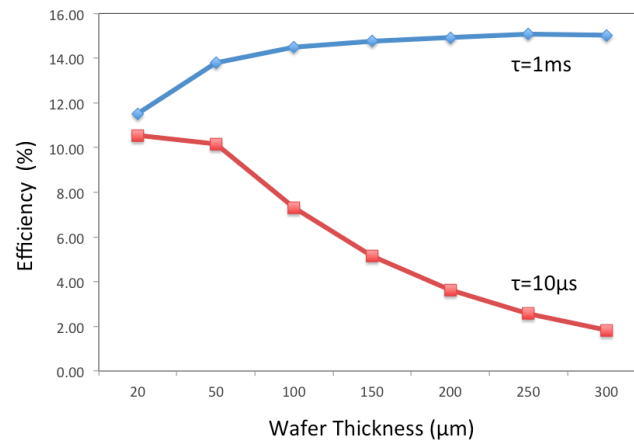


Fig. 10. IBC solar cells efficiency against wafer thickness. For high lifetime wafer, increasing the thickness results in increased efficiency. On the other hand, poor carrier lifetime wafer would result in reduced efficiency as the thickness is increased due to limited diffusion length, L_n .

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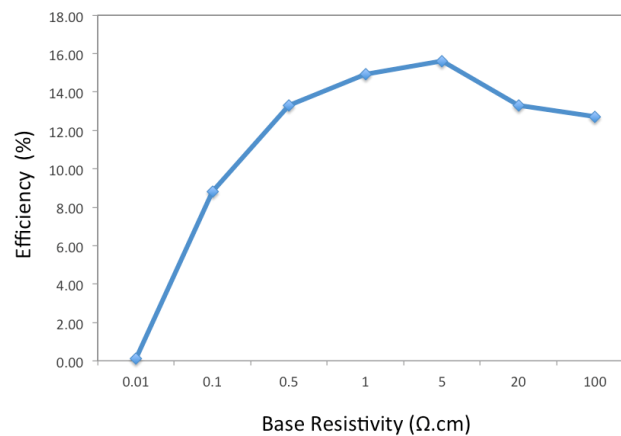


Fig. 11. IBC solar cell efficiency against substrates base resistivity. Selection of a good base substrate resistivity will ensure good performance IBC solar cell.

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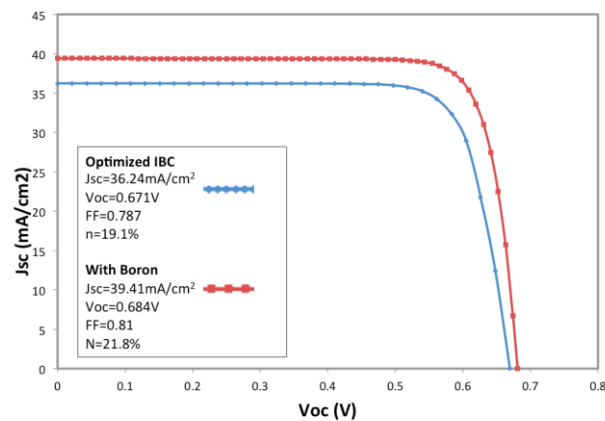


Fig. 12. Shown above is the IV curve of IBC solar cell with optimized doping, geometrical and substrates (red). This is compared to similar structure but with boron as dopant for base region (blue).

IMAGE SIZE: 88 mm/181 mm
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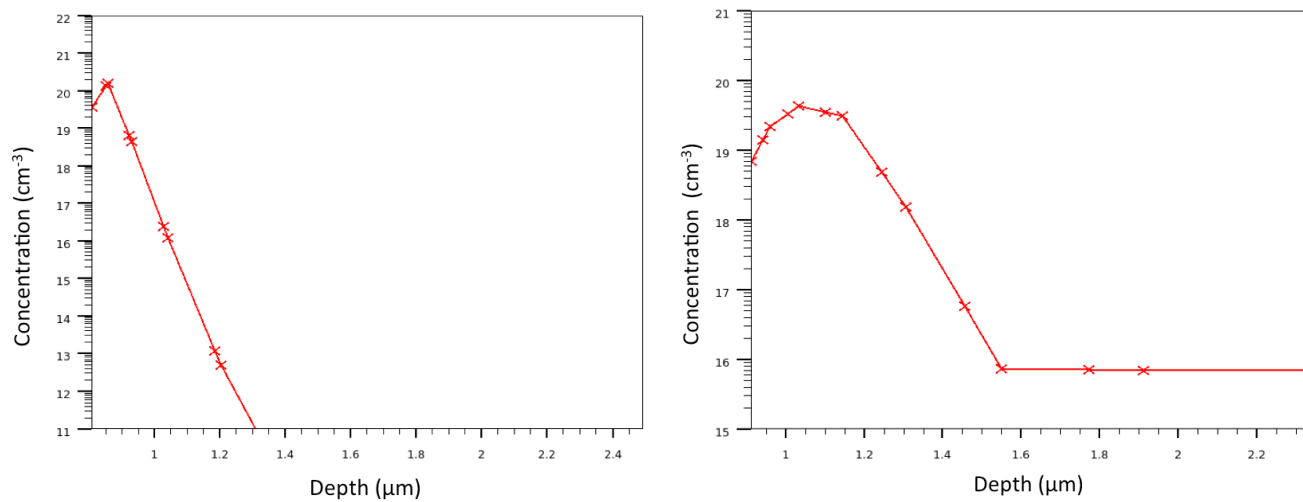


Fig. 13. The doping profile of Aluminum dopants (left) and boron dopants [34]. Aluminum dopant shows shallower profile with high concentration near the surface region.

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 FIGURE AXIS LABEL

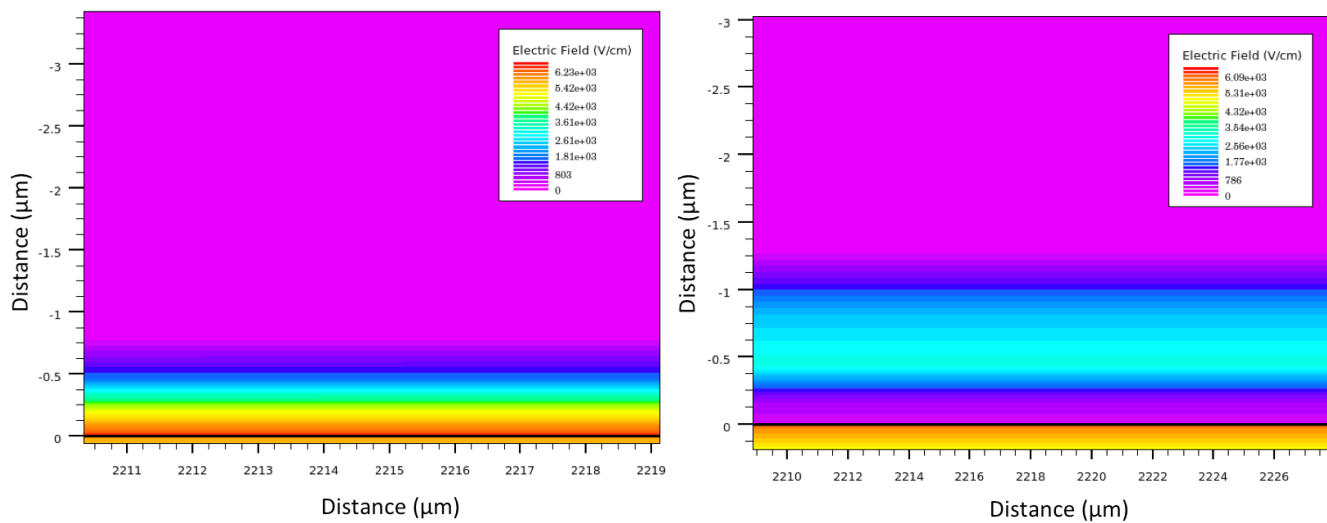


Fig. 14. The electric potential on the base region from Aluminum dopants (left) and boron dopants [34]. Boron dopants show much deeper electric potential compare to aluminum dopants.

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TABLE I
SOLAR CELL PARAMETERS USED FOR SIMULATION OF SCREEN PRINTED IBC SOLAR CELL

Serial No.	Parameters	Value
1.	Wafer	Thickness Type Resistivity Width
		200 μ m p-type 2 Ω .cm 3000 μ m
2.	Front Surface Field (Floating Junction)	Dopants Concentration
		Phosphorous Varied
3.	Emitter	Dopants Concentration Width
		Phosphorous Varied 1000 μ m
4.	Back Surface Field (BSF)	Dopants Concentration Width
		Aluminum Varied 1000 μ m
5.	Back Surface Recombination Velocity (BSRV)	Value
		1000cm/s
6.	Front Surface Recombination Velocity(SRV)	Value
		500cm/s

Attachment J

Optimization of p-type Screen Printed Interdigitated Back Contact Silicon Solar Cell with Two-Dimension Solar Cell Model

Mohd K. Mat Desa^{1,2}

1-Solar
2-School of
3-School of

Ayu Wazira Azhari^{1,3}

Malaysia
Malaysia.
sia.

Abstract— Interdigitated Back Contact (IBC) solar cells have been routinely fabricated with conventional aluminum metallization. However, due to the requirements of multiple patterning layers, the process is still high. In contrast, screen printed IBC solar cells are inexpensive processes utilizing conventional aluminum metallization. Although the screen printed IBC solar cells are inexpensive, however its efficiency is poor. In this paper, constraints on screen printed IBC solar cells are investigated. Two-dimensional model is developed using computer aided design (CAD) software from SILVACO. The device parameters impacting IBC solar cell efficiency including fabrication, configuration, and material. With suitable starting material, the fabrication process, solar cell efficiency is predicted. Higher efficiency is achieved, however, aluminum metallic paste is used for simplification which is not suitable for manufacturing.

Index Term— IBC, Interdigitated back contact, Silicon solar cell, Two-dimension solar cell model.

I. INTRODUCTION

It is well known that the efficiency of conventional silicon solar cell is limited by front surface shadow and series resistive losses. Ideally, the front grid contact and the busbar of conventional silicon solar cell must be minimized to reduce shadowing losses. Unfortunately, reducing the contact grid and busbar dimensions increases ohmic resistive losses. Also, the series resistance issues extend to solar modules where many solar cells are interconnected, this decrease the

to reduce resistive losses. All high conversion efficiency as C modules [2]. Moreover, cell since the solar cells can be configuration. Other advantages resulting in a smaller module comparison with conventional term black/dark appearance IBC integration.

efficiency structures, a major is its complicated fabrication oration, a number of process eeded. For example, separate are used to precisely define ase, emitter contact and base alignment required for the above process slower and expensive. is often fabricated using four to graphy is an expensive process

reducing lithography steps in the fabrication process makes an economic sense [4]. In addition, lithographically-defined emitter and base regions have other disadvantages as well. They require expensive metallization process such as vacuum evaporation or sputtering beam to define the metal contacts.

Recent work has exhibited strong trend towards lithography-free fabrication process of IBC solar cell [5]. These widely different methods include the use of dielectric with laser ablation combined with screen printing [6], diffusion barrier paste [7, 8], diffusion paste [9] and laser scribing [10]. In terms of terminology, these techniques can be categorized under the term “screen printed IBC”

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