UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

TAIWAN SEMICONDUCTOR MANUFACTURING COMPANY LTD.,
Petitioner,

v.

ADVANCED INTEGRATED CIRCUIT PROCESS LLC,
Patent Owner.

IPR2025-00831

U.S. Patent 8,587,076

DECLARATION OF JUNE ANN MUNFORD IN SUPPORT OF PETITION FOR *INTER PARTES* REVIEW OF U.S. PATENT 8,587,076

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Alexandria, VA 22313-1450

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I. Introduction

I, June Ann Munford, do hereby declare as follows:

1. I am over the age of 18, have personal knowledge of the facts set forth herein, and am competent to testify to the same.

2. I have been retained as an expert witness by Goodwin Procter on behalf of Tawain Semiconductor Manufacturing Company Ltd. ("TSMC") for proceedings before the United States Patent and Trademark Office ("USPTO") regarding the authenticity and public availability of certain prior art references discussed in this declaration in relation to U.S. Patent 8,587,076 ("the '076 patent").

3. I am being compensated for my work in this matter at my standard hourly rate of $200.00 per hour and am being reimbursed for any reasonable expenses associated with my work and my testimony in this matter. My statements are objective, and my compensation does not depend on the outcome of this matter.

4. I reserve the right to supplement or amend my opinions in response to any additional evidence, testimony, discovery, argument, and/or other additional information that may be provided or that I may obtain independently after the date of this declaration.

A. Qualifications and Work Experience

5. I earned a Master of Library and Information Science (MLIS) from the University of Wisconsin-Milwaukee in 2009. I have over ten years of experience in the library/information science field. Beginning in 2004, I have served in various positions in the public library sector including Assistant Librarian, Youth Services Librarian and Library Director. I have attached my Curriculum Vitae as Appendix CV.

6. During my career in the library profession, I have been responsible for materials acquisition for multiple libraries. In that position, I have cataloged, purchased and processed incoming library works. That includes purchasing materials directly from vendors, recording publishing data from the material in question, creating detailed material records for library catalogs and physically preparing that material for circulation. In addition to my experience in acquisitions, I was also responsible for analyzing large collections of library materials, tailoring library records for optimal catalog, search performance and creating lending agreements between libraries during my time as a Library Director.

B. MARC

7. I am fully familiar with the catalog record creation process in the library sector. In preparing a material for public availability, a library catalog record describing that material would be created. These records are typically written using

Machine Readable Catalog (herein referred to as "MARC") codes and contain information such as a physical description of the material, metadata from the material's publisher, and date of library acquisition.

8. I am very familiar with MARC, which became the national standard for sharing bibliographic data in the United States by 1971 and the international standard by 1973. MARC is the primary communications protocol for the transfer and storage of bibliographic metadata in libraries. Experts in my field reasonably rely upon MARC records when forming their opinions.

9. A MARC record contains several fields, each identified by a standardized, unique, three-digit code corresponding to the data that follows. (*See,* Appendix XX, Parts VII to X of "Understanding MARC Bibliographic: Machine-Readable Cataloging" (http://www.loc.gov/marc/umb/um07to10.html).) For example, the author of a work is recorded in Field 100, the title/attribution is recorded in Field 245, the publisher is recorded in Figure 260, a book's physical description is record in Field 300, and Field 008 is reserved for denoting the date of creation of the library record itself. As this typically occurs during the process of preparing materials for public access, it is my experience that an item's MARC record indicates the date of an item's public availability.

10. Typically, in creating a MARC record, a librarian would gather various bits of metadata such as book title, publisher and subject headings among others

and assign each value to a relevant numerical field. The 008 field of the MARC record is reserved for denoting the creation of the library record itself. As this is the only date reflecting the inclusion of said materials within the library's collection, it is my experience that an item's 008 field accurately indicates the date of an item's public availability.

C. Scope of this Declaration

11. I have been asked to offer an opinion on the authenticity and public availability date of the following documents:

- Sim, J. H., et al., "Effects of ALD HfO_2 thickness on charge trapping and mobility," Microelectronic Engineering, Vol. 80, pp. 218-221, June 17, 2005 ("Sim")
- Koyama, M., et al., "Effects of Nitrogen in HfSiON Gate Dielectric on the Electrical and Thermal Characteristics," Digest of International Electron Devices Meeting, pp. 849-852, Dec. 8-11, 2002 ("Koyama")

D. Resources Consulted and Evidence Considered

12. I am personally familiar with many online catalogs, databases, and search engines. In preparing this declaration, I used the following resources to search for records:

- Ecosia – A search engine aggregator that provides web results for search queries from several sources, including Bing and Google. This

search engine is capable of advanced search queries and provides results in several multimedia formats. I used Ecosia to search for each document authenticated in this declaration to confirm publication information such as journal title, issue number, proceedings title, year of publication, name of publisher and related international standard numbers such as ISBN and ISSN.

- Worldcat – A search engine that indexes library holdings across thousands of different library collections. This search engine is capable of advanced search queries and provides results describing the library holdings of thousands of libraries, museums and non-profits. I used Worldcat to help source library copies of each reference.
- Library Catalogs – For each library holding, I used the associated library catalog to locate MARC records and library holdings for each reference included in this declaration. The two catalogs referenced in this declaration are the Penn State University Library Catalog and the Linda Hall Library Catalog. These catalogs function similarly to search engines, capable of advanced search queries and detailed results filtering.

13. In preparing this declaration, I have also reviewed the documents referenced below and any other document that I mention herein. Each of the listed

documents is a type of material that experts in my field would rely upon when forming their opinions.

II. Authenticity and Public Availability of Sim

A. MARC Record

14. Attached hereto as Appendix SIM01 is a true and correct copy of the MARC record for Microelectronic Engineering as held by the Penn State University Library. I secured this record myself from the library's public catalog. The MARC record contained within Appendix SIM01 accurately describes the title, publisher and ISSN number of Microelectronic Engineering. The Showing Results field present on page 3 of this record indicates the library's collection includes the June 17, 2005 issue of Microelectronic Engineering containing "Effects of ALD HfO2 thickness on charge trapping and mobility".

15. The 008 field of the MARC record in Appendix SIM01 indicates the date of record creation. The 008 field of Appendix SIM01 indicates the Penn State University Library first acquired Microelectronic Engineering as of May 5, 1998 and held the journal in perpetuity until the publication of "Effects of ALD HfO2 thickness on charge trapping and mobility". Considering this information, it is my determination that Microelectronic Engineering June 17, 2005 and therefore "Effects of ALD HfO2 thickness on charge trapping and mobility" was made available to the public shortly after its initial publication in June 17, 2005.

B. Authentication

16. Attached hereto as Appendix SIM02 is a true and correct copy of "Effects of ALD HfO2 thickness on charge trapping and mobility" by J.H. Sim, et al. as published in the Microelectronic Engineering, June 17, 2005. I secured this record myself from collection of the Penn State University's Library.

17. The document submitted as TSMC-1024 in the *inter partes* review of the '076 patent is the same as the copy of Sim provided as SIM02. In comparing TSMC-1024 to Appendix SIM02, it is my determination that TSMC-1024 is a true and correct copy of "Effects of ALD HfO2 thickness on charge trapping and mobility" by J.H. Sim, et al as published in Microelectronic Engineering.

III. Authenticity and Public Availability of Koyama

A. MARC Record

18. Attached hereto as Appendix KOYAMA01 is a true and correct copy of the MARC record for Proceedings of the 2002 International Electron Devices Meeting as held by the Linda Hall Library. I secured this record myself from the library's public catalog. The MARC record contained within Appendix KOYAMA01 accurately describes the title, publisher and ISBN number of Proceedings of the 2002 International Electron Devices Meeting.

19. The 008 field of the MARC record in Appendix KOYAMA01 indicates the date of record creation. The 008 field of Appendix KOYAMA01 indicates the

Linda Hall Library first acquired Proceedings of the 2002 International Electron Devices Meeting as of January 6, 2003. Considering this information, it is my determination that Proceedings of the 2002 International Electron Devices Meeting and therefore "Effects of Nitrogen in HfSiON Gate Dielectric on the Electrical and Thermal Characteristics" was made available to the public shortly after its initial publication as of January 6, 2003.

B. Authentication

20. Attached hereto as Appendix KOYAMA02 is a true and correct copy of "Effects of Nitrogen in HfSiON Gate Dielectric on the Electrical and Thermal Characteristics" by Masato Koyama, et al. as published in the Proceedings of the 2002 International Electron Devices Meeting. I secured this record myself from collection of the Linda Hall Library.

21. The document submitted as TSMC-1029 in the *inter partes* review of the '076 patent is the same as the copy of Koyama provided as KOYAMA02. In comparing TSMC-1029 to Appendix KOYAMA02, it is my determination that TSMC-1029 is a true and correct copy of "Effects of ALD HfO2 thickness on charge trapping and mobility" by Masato Koyama, et al as published in Proceedings of the 2002 International Electron Devices Meeting.

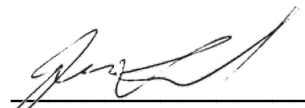
IV. Conclusion

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

23. I declare that all statements made herein of my knowledge are true, that all statements made on information and believe are believed to be true, and that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Executed on April 3, 2025 in Pittsburgh, Pennsylvania.

Respectfully submitted,



June Ann Munford

APPENDIX CV

June A. Munford
Curriculum Vitae

Education

University of Wisconsin-Milwaukee - MS, Library & Information Science, 2009
Milwaukee, WI

- Coursework included cataloging, metadata, data analysis, library systems, management strategies and collection development.
- Specialized in library advocacy, cataloging and public administration.

Grand Valley State University - BA, English Language & Literature, 2008
Allendale, MI

- Coursework included linguistics, documentation and literary analysis.
- Minor in political science with a focus in local-level economics and government.

Professional Experience

Researcher / Expert Witness, October 2017 – present
Freelance ● Pittsburgh, Pennsylvania & Grand Rapids, Michigan

- Material authentication and public accessibility determination. Declarations of authenticity and/or public accessibility provided upon research completion. Experienced with appeals and deposition process.

- Research provided on topics of public library operations, material publication history, digital database services and legacy web resources.

- Past clients include Alston & Bird, Arnold & Porter, Baker Botts, Fish & Richardson, Erise IP, Irell & Manella, O'Melveny & Myers, Perkins-Coie, Pillsbury Winthrop Shaw Pittman and Slayden Grubert Beard.

Library Director, February 2013 - March 2015
Dowagiac District Library ● Dowagiac, Michigan

- Executive administrator of the Dowagiac District Library. Located in

Southwest Michigan, this library has a service area of 13,000, an annual operating budget of over $400,000 and total assets of approximately $1,300,000.

● Developed careful budgeting guidelines to produce a 15% surplus during the 2013-2014 & 2014-2015 fiscal years while being audited.

● Using this budget surplus, oversaw significant library investments including the purchase of property for a future building site, demolition of existing buildings and building renovation projects on the current facility.

● Led the organization and digitization of the library's archival records.

● Served as the public representative for the library, developing business relationships with local school, museum and tribal government entities.

● Developed an objective-based analysis system for measuring library services - including a full collection analysis of the library's 50,000+ circulating items and their records.

November 2010 - January 2013
Librarian & Branch Manager, Anchorage Public Library ● Anchorage, Alaska

● Headed the 2013 Anchorage Reads community reading campaign including event planning, staging public performances and creating marketing materials for mass distribution.

● Co-led the social media department of the library's marketing team, drafting social media guidelines, creating original content and instituting long-term planning via content calendars.

● Developed business relationships with The Boys & Girls Club, Anchorage School District and the US Army to establish summer reading programs for children.

June 2004 - September 2005, September 2006 - October 2013
Library Assistant, Hart Area Public Library
Hart, MI

● Responsible for verifying imported MARC records and original MARC

cataloging for the local-level collection as well as the Michigan Electronic Library.

● Handled OCLC Worldcat interlibrary loan requests & fulfillment via ongoing communication with lending libraries.

Professional Involvement

Alaska Library Association - Anchorage Chapter
- Treasurer, 2012

Library Of Michigan
- Level VII Certification, 2008
- Level II Certification, 2013

Michigan Library Association Annual Conference 2014
- New Directors Conference Panel Member

Southwest Michigan Library Cooperative
- Represented the Dowagiac District Library, 2013-2015

Professional Development

Library Of Michigan Beginning Workshop, May 2008
Petoskey, MI
- Received training in cataloging, local history, collection management, children's literacy and reference service.

Public Library Association Intensive Library Management Training, October 2011
Nashville, TN
- Attended a five-day workshop focused on strategic planning, staff management, statistical analysis, collections and cataloging theory.

Alaska Library Association Annual Conference 2012 - Fairbanks, February 2012
Fairbanks, AK
- Attended seminars on EBSCO advanced search methods, budgeting, cataloging, database usage and marketing.

Depositions

2019 ● Fish & Richardson

Apple v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282 and 39521-00421IP2)

2019 ● Erise IP

Implicit, LLC v. Netscout Systems, Inc (Civil Action No. 2:18-cv-53-JRG)

2019 ● Perkins-Coie

Adobe Inc. v. RAH Color Technologies LLC (Cases IPR2019-00627, IPR2019-00628, IPR2019-00629 and IPR2019-00646)

2020 ● O'Melveny & Myers

Maxell, Ltd. v. Apple Inc. (Case No. 5:19-cv-00036-RWS)

2021 ● Pillsbury Winthrop Shaw Pittman LLP

Intel v. SRC (IPR2020-1449)

2022 ● Perkins-Coie

Realtek v. Future Link (IPR2021-01182)

2023 ● Fish & Richardson

Neuroderm Ltd. v. Abbvie, Inc (Case No. PGR2022-00040)

2023 ● Fish & Richardson

Nearmap US Inc. v. Pictometry International Corp. (IPR2022-00735)

2023 ● Fish & Richardson

Samsung Electronics v. MemoryWeb LLC (Case No. 39843-0136PS1)

2023 ● Pillsbury Winthrop Shaw Whitman LLP

Gravel Rating Systems v. Costco Wholesale Corp. (Civil Action No. 4:21-cv-149-ALM)

Limited Case and Clientele History

Alston & Bird

- Ericsson

  v. Collision Communications (IPR2022-01233)

- Nokia

  v. Neptune Subsea, Xtera (Case No. 1:17-cv-01876)

- Universal Electronics Inc

  v. Roku Inc (IPR2022-00818)

Arnold & Porter

- Ivantis

  v. Glaukos (Case No. 8:18-cv-00620)

- Samsung

  v. Jawbone (Case No. 2:21-cv-00186)

Benesch Friedlander Coplan & Aronoff

- Voyis

  v. Cathx (Case No. 5:21-cv-00077-RWS)

Erise I.P.

- Apple
  - v. Ericsson Inc. (IPR2022-00715)
  - v. Future Link Systems (IPRs 6317804, 6622108, 6807505, and 7917680)
  - v. INVT (Case No. 20-1881)
  - v. Navblazer LLC (IPR2020-01253)
  - v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282, 39521-00421IP2)
  - v. Quest Nettech Corp (Case No. 2:19-cv-00118-JRG)
  - v. Telefonaktiebolaget LM Ericsson (IPR2022-00275)
- Fanduel
  - v. CGT (Case No. 19-1393)
- Garmin
  - v. Phillips North America LLC (Case No. 2:19-cv-6301-AB-KS)
- Netscout
  - v. Longhorn HD LLC (Case No. 2:20-cv-00349)
  - v. Implicit, LLC (Civil Action No. 2:18-cv-53-JRG)
- Sony Interactive Entertainment LLC
  - v. Bot M8 LLC (IPR2020-01288)
  - v. Infernal Technology LLC (Case No. 2:19-CV-00248-JRG)
- Unified Patents

v. GE Video Compression (Civil Action No. 2:19-cv-248)

Fish & Richardson

- Apple
  - v. AliveCor (3:21-cv-03958)
  - v. LBS Innovations (Case No. 2:19-cv-00119-JRG-RSP)
  - v. Koss Corporation (IPR2021-00305)
  - v. Masimo (IPR 50095-0012IP1, 50095-0012IP2, 50095-0013IP1, 50095-0013IP2, 50095-0006IP1, 50095-0135IP1)
  - v. Neonode (Case No. 21-cv-08872-EMC)
  - v. Qualcomm (IPR2018-001281, 39521-00421IP, IPR2018-01282, 39521-00421IP2)
- Dell
  - v. Neo Wireless (IPR2022-00616)
- Dish Network
  - v. Entropic Communications, LLC (Case No. 2:2023-CV-01043)
  - v. Realtime Adaptive Streaming (Case No. 1:17-CV-02097-RBJ)
  - v. TQ Delta LLC (Case No. 18-1798)
- Evapco Dry Cooling
  - v. SPG Dry Cooling (IPR2021-00688)
- Genetec
  - v. Sensormatic Electronics (Case No. 1:20-CV-00760)
- Huawei

v. Bell Northern Research LLC (IPR2019-01174)

- Kianxis

  v. Blue Yonder (Case No. 3:20-cv-03636)

- LG Electronics

  v. Bell Northern Research LLC (Case No. 3:18-cv-2864-CAB-BLM)

- Metaswitch

  v. Sonus Networks (IPR2018-01719)

- Microsoft

  v. Throughputer Inc (IPR2022-00757)

- Mom Enterprises

  v. Ddrops Company (Case No. 1:22-cv-00332)

- MLC Intellectual Property

  v. MicronTech (Case No. 3:14-cv-03657-SI)

- Nearmap Inc

  v. EagleView Technologies (IPR2022-01009)

- Neuroderm Ltd.

  v. Abbvie, Inc (Case No. PGR2022-00040)

- Realtek Semiconductor

v. Future Link (IPR2021-01182)

- Quectel
  - v. Koninklijke Philips (Case No. 1:20-cv-01710)

- Samsung
  - v. Aire Technology (IPR2022-00877)
  - v. Bell Northern Research (Case No. 2:19-cv-00286-JRG)
  - v. Communication Technologies Inc (IPR2022-01221)
  - v. Jawbone Innovations (IPR2022-00865)
  - v. MemoryWeb LLC (IPR2022-00885)
  - v. Dodots Licensing Solutions (IPR2023-00701)
  - v. Telefonaktiebolaget LM Ericsson (IPR2021-00615)

- Texas Instruments
  - v. Vantage Micro LLC (IPR2020-01261)

- Xilinx
  - v. Sentient Sensors LCC (Case No. 1:22-cv-00173)

Irell & Manella

- Curium

O'Melveny & Myers

- Apple
  - v. Maxell (Case No. 5:19-cv-00036-RWS)

- Micron Technology Inc.

  v. Besang Inc (IPR2023-00900)

- Samsung

  v. Daedalus Prime LLC (1335 Investigation)

Perkins-Coie

- Heru Industries

  v. The UAB Research Foundation (IPR2022-01148)

- Intel Corporation

  v. BitMICRO (Case No. 5:23-cv-00625)

- Realtek Semiconductor

  v. Future Link (IPR2021-01182)

- Twitter Inc

  v. VOIP-Pal.com (Case No. 3:20-cv-02397-JD)

- TCL Industries

  v. Koninklijke Philips NV (IPR2021-00495, IPR2021-00496 and IPR2021-00497)

Pillsbury Winthrop Shaw Pittman

- Intel

  v. FG SRC LLC (Case No. 6:20-cv-00315)

- Gravel Rating Systems

v. Costco (Case No. 4:21-cv-149)
v. Lowe's Home Centers (Case No. 4:21-cv-150)
v. T-Mobile USA (Case No. 4:21-cv-152)
v. Kohl's Inc. (Case No. 4:21-cv-258)
v. Under Armor (Case No. 4:21-cv-356)

Quinn Emanuel

- Wolfspeed

    v. The Trustees of Purdue University (Case No. 1:2021-cv-00840)

Stern, Kessler, Goldstein & Fox

- Preliminary Research

Sheppard, Mullin, Richter & Hampton LLP

- Cadence Design Systems Inc.

    v. Semiconductor Design Technologies (Case No. 3:23-cv-01001)

APPENDIX SIM01

MARC View

LEADER 02007nas a2200457 a 4500				
001 46030333				
003 SIRSI				
005 20241114090046.0				
006 m o d				
007 cr n				
008 980505c19839999ne x pss 0 a0eng c				
010				a| 2005233292
016	7			a| 1497065-X 2| DE-600
019				a| DO NOT EDIT this 360 MARC RECORD
022				a| 1873-5568 l| 0167-9317 y| 0167-9317
030				a| MIENEF
035				a| (WaSeSS)ssj0016408
040				a| OH1 b| eng c| OH1 d| OCL d| OCLCQ d| GUA d| VRC d| U9S d| CLU d| GUA d| OCLCQ d| CUD d| OCLCQ d| OCLCO d| OCLCQ d| OCLCE d| SFB d| SSJ d| CSU d| OCLCF d| OCLCO d| OCLCQ d| UHL d| LIP d| OCLCQ d| VT2 d| UKSSU d| OCLCO d| OCLCQ d| UAB d| WaSeSS
042				a| pcc a| dlr
050	1	4		a| TK7871.85
130	0			a| Microelectronic engineering (Online)
222			0	a| Microelectronic engineering b| (Online)
245	1	0		a| Microelectronic engineering h| [electronic resource].
260				a| Amsterdam : b| Elsevier Science Pub. Co., c| 1983-
310				a| Irregular
362	0			a| Vol. 1, issue 1 (Sept. 1983)-
500				a| Title from contents screen (ScienceDirect, viewed Nov. 4, 2005).
515				a| Some issues combined.
538				a| Mode of access: World Wide Web.
583	1			a| digitized c| 2011 h| HathiTrust Digital Library l| committed to preserve 2| pda 5| MiAaHDL
588				a| Latest issue consulted: Vol. 86, issue 10 (Oct. 2009) (viewed Aug. 3, 2009).
650			0	a| Semiconductors x| Design and construction v| Periodicals.
650			0	a| Semiconductor industry v| Periodicals.
650			0	a| Microelectronics v| Periodicals.
650			0	a| Nanoelectronics v| Periodicals.
650			0	a| Semiconductor industry x| Periodicals.
655			0	a| Electronic journals.
776	0	8		i| Print version: t| Microelectronic engineering x| 0167-9317 w| (DLC) 89648025 w| (OCoLC)10329408
856	4	0		u| http://SK8ES4MC2L.search.serialssolutions.com/?V=1.0&L=SK8ES4MC2L&S=JCs&C=MICRENG&T=marc
910				a| CONSER online
949				a| Electronic resource w| ASIS c| 1 i| 46030333-1001 l| ONLINE m| ONLINE r| Y s| Y t| ONLINE u| 11/16/2024 o| .STAFF. 360 MARC

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Microelectronic engineering [electronic resource].

Uniform Title: Microelectronic engineering (Online)

Published: Amsterdam : Elsevier Science Pub. Co., 1983-

Access Online

serialssolutions.com

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Dates of Publication and/or Sequential Designation

Vol. 1, issue 1 (Sept. 1983)-

Subject(s)

Semiconductors—Design and construction—Periodicals

Semiconductor industry—Periodicals

Microelectronics—Periodicals

Nanoelectronics—Periodicals

Genre(s)

Electronic journals

ISSN

1873-5568

Publication Frequency

Irregular

Note

Title from contents screen (ScienceDirect, viewed Nov. 4, 2005).

Special Numbering

Some issues combined.

Technical Details

Mode of access: World Wide Web.

Action Note

digitized 2011 HathiTrust Digital Library committed to preserve

View MARC record | catkey: 46030333

PennState

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Title begins with Search

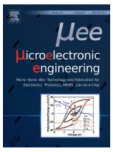
Show more search options ▼

Showing results 1 through 1 of 1

for the search: "MICRENG"

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Limit by: Peer Reviewed | Open Access



Microelectronic engineering

ISSN: 0167-9317

Peer Reviewed

1983 to 1994 in Backfile Package - Computer Science (Legacy) [YCS]
Backfile Package - Engineering and Technology [YEN]
Backfile Package - Materials Science [YMS]
Backfile Package - Physics General (Legacy) [YPA]
Backfile Package - Physics General including Supplement 1 [YUG]

09/01/1983 to Present in ScienceDirect Journals

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APPENDIX SIM02

Available online at www.sciencedirect.com
SCIENCE DIRECT®
Microelectronic Engineering 80 (2005) 218–221
MICROELECTRONIC ENGINEERING
www.elsevier.com/locate/mee

Effects of ALD HfO_2 thickness on charge trapping and mobility

J. H. Sim[1,3], S.C. Song[1], P.D. Kirsch[1,2],C. D. Young[1], R. Choi[1], D. L. Kwong[3], B. H. Lee[1,2] and G. Bersuker[1]

[1] *SEMATECH, 2706 Montopolis Drive, Austin, TX 78741, USA,* [2] *IBM assignee*
[3] *The University of Texas at Austin, USA*
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Abstract

The effects of HfO_2 thickness on charge trapping and mobility were investigated. The impact of fast transient electron trapping on DC measurements results in underestimating channel carrier mobility. Scaling the physical thickness of the HfO_2 dielectric causes less charge trapping and higher mobility. A HfO_2-based high-k solution requires fine-tuning the thickness of the high-k film to maintain a balance between electron trapping in thicker films and increased leakage current in thinner films.

Keywords: charge trapping; mobility; high-k

1. Introduction

Hafnium-based high-k dielectrics and metal gate electrodes have been aggressively investigated to ensure continued scaling of CMOS technology [1-2], but several drawbacks such as low mobility and charge trapping have been identified [3-7]. Even though several process modifications such as nitridation and silicate formation have been proposed to overcome the limitations of high-k dielectrics, the effect of these changes has not been investigated systematically [8-11]. Recently, the reduction of transient charge trapping was proposed as a way to improve the quality of high-k dielectrics [3]. Transient charging, which is generally not observed in SiO_2, complicates the evaluation of the properties of high-k gate stacks because the mobility of the high-k device is usually underestimated when DC I_d-V_g curves are used for mobility extractions. To overcome the limitations of this conventional methodology, a pulsed I_d-V_g method has been proposed to extract close to intrinsic channel mobility of high-k gate transistors [6-7, 12-14]. Using this new understanding and new methodologies, we have systematically evaluated the effects of high-k film thickness on charge trapping and channel carrier mobility and demonstrated that scaling the high-k dielectric is a simple, but very effective means of improving mobility and other reliability characteristics.

2. Experimental

To investigate the effects of high-k thickness, transistor gate stacks were fabricated with 20–40Å thick atomic layer deposition (ALD) HfO_2 films. The gate electrode was 10nm ALD TiN with a 150nm polysilicon capping layer. Equivalent oxide thickness

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(EOT) and mobility values were extracted from the capacitance-voltage (C-V) and current-voltage (I-V) data using the North Caroline State University (NCSU) model. For mobility extraction, both DC and pulsed I_d-V_g data were used [12]. Pulse rise/fall and width times were varied to evaluate the effects of charge trapping on channel mobility. For the charge trapping study, threshold voltage shifts and drain current changes were estimated from the pulsed I_d-V_g measurements. I-V characteristics were measured on 10×1μm (WxL) field-effect transistors (FETs). The physical thickness of the HfO_2 and interfacial sub-oxide layer were verified by transmission electron microscopy (TEM) measurements.

3. Results and Discussion

Raw C-V data show capacitance scaling with physical thicknesses of 18Å, 25Å, and 33Å as estimated by TEM measurements (Fig. 1), which correlate well with the extracted EOT values of 9.5Å, 10.6Å, and 11.8Å, respectively (Fig. 2).

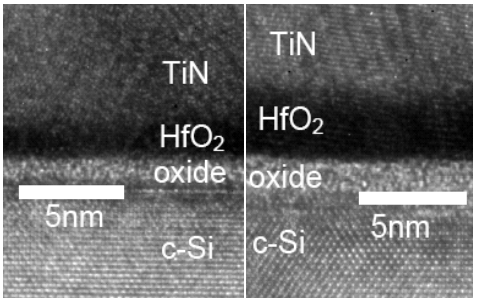


Figure. 1: TEM images of the HfO_2 gate stacks of 18Å and 33Å physical thickness.

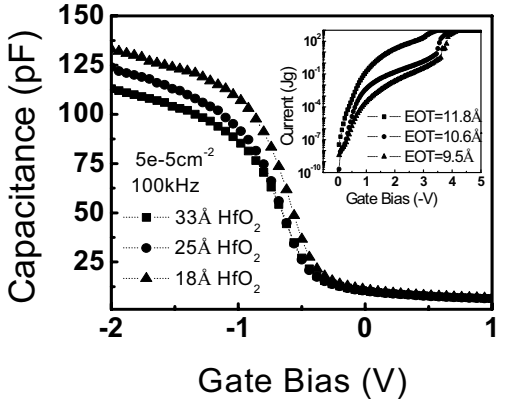


Figure. 2: C-V and gate leakage current (inserted) data for the studied dielectric films.

In all stacks, the effective k value of the nitride high-k film is about 24. The EOT of the interfacial layer is estimated as ~ 6.5Å due to the greater k value of the interfacial oxide layer [13]. Gate leakage current also scales with the physical thickness of HfO_2 (inset of Fig. 2). The gate leakage current values measured in this study roughly match historical data in the literature and our own work, indicating these samples are very close to typical HfO_2 dielectrics (Fig. 3).

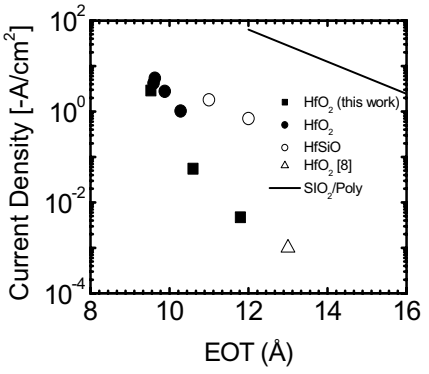


Figure. 3: Current density vs. EOT data for the HfO_2 gate stacks studied in this work and published data at V_{fb}-1V.

To examine fast charge trapping effects, the time dependence of the drain current induced by the 1.4V, 100μs width pulse (applied to the drain current and to NMOS with various HfO_2 thicknesses) was monitored (Fig. 4). In this plot, the reduction in time-dependent drain current is primarily due to the charge trapping-induced V_{th} shift. Even within 100μs, a 33Å HfO_2 sample shows significant current reduction while a 18Å HfO_2 sample is free from transient charging within the detection limits.

Effective mobility values extracted from DC and pulsed I_d-V_g measurements are plotted in Fig. 5. DC mobility decreases as the HfO_2 becomes thicker. This result can be interpreted using different models. For example, a fixed charge theory attributes this result to increased bulk charge with thicker HfO_2 samples. A phonon scattering theory attributes it to a greater contribution from phonon scattering. However, neither model can explain the dependence of the reduced drain current on time, which is the signature of a dynamic charging process. The

dynamic analysis of I_d (V_g) hysteresis was proposed in high-k dielectric devices [15].

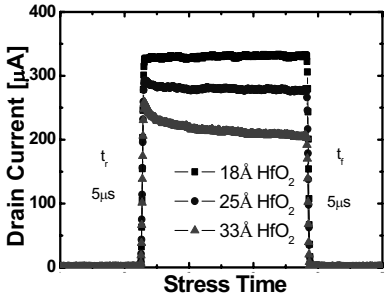


Figure. 4: Variation of the drain current during the pulsed I_d-V_g measurements (pulse width [PW]= 100μs).

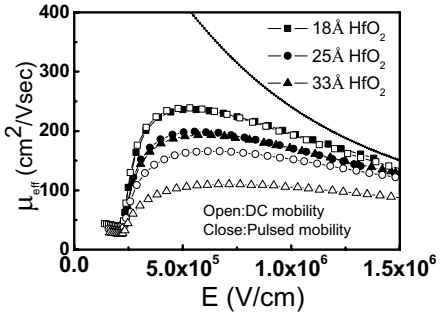


Figure. 5: Mobility vs. effective electrical field dependencies for different HfO_2 film thicknesses extracted from DC and pulsed I_d-V_g measurement.

HfO_2 thickness	18Å	25Å	33Å
EOT(Å)	9.5	10.6	11.8
Jg (A/cm^2) (at V_{fb}-1V)	2.88	5.5 e-2	4.7 e-4
DC/Pulse mobility (1MV/cm)	194/ 197	153/ 171	105/ 170
Peak Nit (x10^{10}cm^{-2})	2.9	2	2

Table 1: Electrical characteristics of the studied high-k stacks.

Mobility values extracted from the pulsed I_d-V_g dependencies are much higher than the DC mobility for 25Å and 33Å HfO_2 samples; for the 18Å sample, the difference between DC mobility and pulsed mobility is minimal. Also, the mobility value of the 18Å sample is very close to universal mobility [14]. Table. 1 summarizes the electrical characteristics of the studied gate stack. It is interesting to note that the mobility values for the pulse (which is free from the effect of charge trapping) are higher for thinner dielectric films. Since the interface state density is similar in all high-k samples (Table. 1), the interface quality of these HfO_2 stacks is not the main reason for the higher mobility of the 18Å sample.

The transient charging model can explain these results in a systematic way. Fast electron trapping can effectively increase the magnitude of the threshold voltage during the DC measurements of the drain current, resulting in overestimation of the inversion charge and, subsequently, underestimation of intrinsic channel carrier mobility [4].

The dependence of drain current on pulse magnitude shows less charge trapping when the applied gate voltage and HfO_2 thickness decrease (Fig. 6). The thinnest HfO_2 film does not exhibit a reduction in drain current at any of the applied voltages, indicating no appreciable charge trapping exists in the microsecond pulse time range.

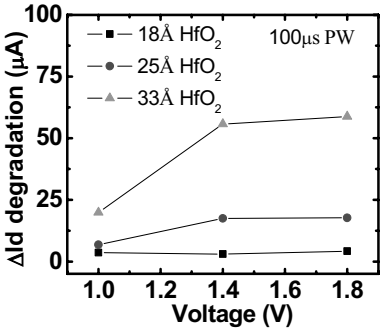


Figure. 6: Drain current reduction vs. amplitude of the 100μs pulse.

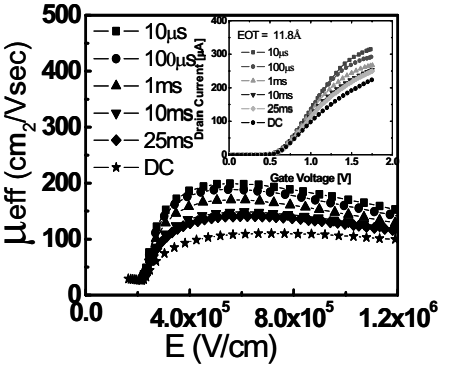


Figure. 7: Channel mobility of the 33Å gate stack extracted from the pulsed I-V data of different pulse rise time.

The charge trapping effect also depends on charging time. As can be seen in the insert in Fig. 7, I_{dlin} (at V_g=1.8V V_d=0.05V) is a function of pulse rise time indicating that charge trapping occurs on a time scale of less than 10μs. Channel mobility of the 33Å gate stack follows the pulsed I-V data of different pulse rise time.

The ratio of the pulsed I_d-V_g and DC drain currents in the linear regime shows a significant gain with thicker HfO_2 (Fig. 8). On the other hand, the gain in the18Å HfO_2 sample is less than 1%, pointing to a similar charge trapping effect caused by the fast pulse and DC I_d-V_g measurements. The 18Å HfO_2 stack demonstrated less V_{th} shift under DC constant voltage stress than did thicker films (Fig. 9). Since the electric field in the thin film during the stress was higher than in thicker films by 2MV/cm, one may conclude that thinner films demonstrate better device stability with respect to charge trapping.

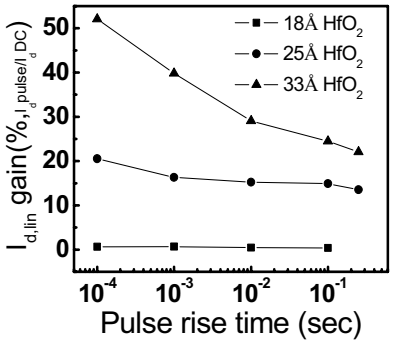


Figure. 8: Ratio of the pulse and DC drain currents in the linear regime vs. pulse width time.

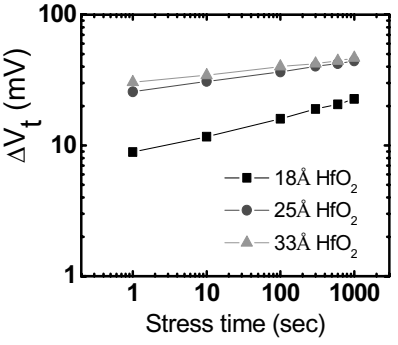


Figure. 9: Under the same constant voltage stress condition (Vg=1.8V), 18Å HfO_2 device show less threshold voltage shift.

The threshold voltage shift in thin film devices during constant voltage stress (CVS) indicates that charge traps still exist in thinner films although their effect on V_{th} shift is much less. Therefore, the HfO_2-based high-k solution requires fine-tuning the thickness of the high-k film to maintain a balance between electron trapping in thicker films and increased leakage current in thinner films. Plasma treatments, surface nitridation, and other processing techniques can be used to further reduce charge trapping in thin high-k dielectric gate stacks to improve device stability.

4. Summary

The effects of HfO_2 thickness on charge trapping and mobility were investigated. The impact of fast transient electron trapping on DC measurements results in underestimating channel carrier mobility. Scaling the physical thickness of the HfO_2 dielectric to below 20Å causes less charge trapping and higher mobility.

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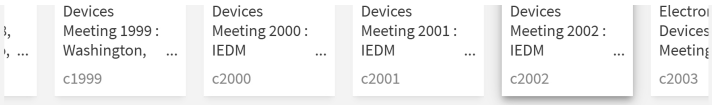
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Effects of Nitrogen in HfSiON Gate Dielectric on the Electrical and Thermal Characteristics

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Abstract

The effects of the nitrogen in the HfSiON gate dielectric on the electrical and thermal properties of the dielectric were investigated. It is clearly demonstrated that nitrogen enhances the dielectric constant of silicates. High dielectric constants of the HfSiON are maintained and boron penetration is substantially suppressed in the HfSiON during high temperature annealing. These properties are ascribed to the homogeneity of the bond structure in the film containing nitrogen through high temperature annealing.

Introduction

Hf(Zr) silicates are considered to be prospective high-K materials due to their modest dielectric constants and good interface properties [1,2]. However, for its use as the first generation high-K dielectrics for low-power CMOS, they must meet following requirements: 1)equivalent oxide thickness (EOT) of 12 to 20 Å with the gate leakage of 1 to 100 mA/cm^2 @|Vdd = 1 V| [3] and 2) compatibility with the conventional CMOS process. There are following thermal stability concerns with regard to these silicates: 1) phase separation at high temperatures and 2) penetration of B into the film at high temperatures. Recently, HfSiON gate dielectric with excellent thermal stability has been proposed [4-6].

In this study, the effects of nitrogen on the improved thermal stability and electrical characteristics of this dielectric were investigated. The nitrogen incorporated in the HfSiON enhances the dielectric constant of the film. It was found that the dielectric constant was retained through 1000°C annealing for HfSiON, while it decreased severely without N. A poly-Si/HfSiON/Si stack was stable at temperatures up to 1100°C, and, the reduction in leakage current relative to SiO_2 was more than three orders of magnitude for HfSiON. Boron penetration through the film was also suppressed. These properties were found to be due to the nitrogen atoms maintaining the homogeneities of the film through the high temperature annealing.

Structural and electrical characteristics of HfSiON

HfSiON films with a wide composition range were deposited on HF-treated Si substrates by co-sputtering of Hf and Si in an $Ar/N_2/O_2$ ambient. An investigation of the bonding states of the as-sputtered HfSiON films (Hf/Hf+Si = 33%, N = 27at.%, 10 nm thick) indicated that there were no undesirable metallic bonds (Hf-Hf, Hf-Si, and Si-Si) (Figs.1(a),(b)). Si-O-Hf bonding, which is unique to Hf-silicate [1], is the major component in the O1s spectrum (Fig.1(c)), indicating that the HfSiON film is microscopically homogeneous. Fig.1(d) reveals that N-O, N-N, and N-H bonds exist in the as-deposited film; however, these are completely eliminated by annealing at 1000°C, leaving only strong Si-N bonds. The bond configuration of HfSiON is depicted schematically in Fig.2 .

To investigate the role of the N in HfSiON in the electrical and structural stability of HfSiON, the nitrogen concentration [N] of the film was varied from 5 to 30at.% and the Hf/Hf+Si ratio was also changed as indicated in Table 1. The dielectric constants (K) of HfSiON films were precisely evaluated by analyzing the relationship between the physical thickness of HfSiON (determined by TEM or ellipsometry) and the capacitance equivalent thickness (CET) as shown in Fig.3. Fig.4 shows dielectric constants as a function of the Hf/Hf+Si ratio for various [N]. As can be seen, a higher Hf content leads to a higher K-value. Note that though the dielectric constant increases slightly, it increases almost continuously with [N] in HfSiON films. The highest value of the dielectric constant, approximately 13, was obtained for Hf/Hf+Si = 40% and [N] = 23at.%. The nitrogen atoms in HfSiON may enhance the electronic polarization as well as the ionic polarization, both of which contribute to the enhancement of the dielectric constant. The increase of electronic polarization of the film due to the incorporation of N was confirmed by refractive index measurement (Fig.5).

One of the most significant advantages of HfSiON is the inhibition of degradation of K-value with high temperature annealing [7,8] (shown in Fig.6). This is due to the structural stability of HfSiON, which is discussed later. Fig.7 shows the improvement of the C-V curves of Au/HfSiON/p-Si capacitors resulting from the post-deposition annealing (PDA) of HfSiON. The large hysteresis and large Vfb shift for the film before PDA indicate the existence of undesirable defects in the film. It was demonstrated that the PDA process substantially removed these defects without CET degradation (Fig.7). PDA also decreased

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the leakage current through the film drastically. The leakage current for the film after PDA was lower than that of the leakage current for SiO_2 by three orders over a wide range of [N] (Fig.8).

Role of the nitrogen in HfSiON film in improving the microscopic homogeneity of the film

High [N] in HfSiON (Hf/Hf+Si = 20% to 26%) leads to a homogeneous film structure after 1000°C annealing (Fig.9). Incorporation of even 5at.% nitrogen reduced the size of crystallized HfO_2 grains in the film (Fig.9(b)). In accordance with the plan-view TEM results, the crystalline peak of orthorhombic HfO_2 diminished at around [N] = 16at.% (Fig.10). Note, however, that at [N] = 16at.%, Hf-rich regions (dark spots) are still observed due to the phase separation (Fig.9(c)). It was demonstrated that a fully homogeneous film structure could be obtained at [N] = 30at.%. For this film, annealing at 1000°C in N_2 did not reduce the Si-O-Hf bond chains (Fig.11). Annealing of the HfSiON film in O_2, however, depleted the nitrogen at the surface of the film (XPS, data not shown) and led to the severe reduction of the Si-O-Hf peak intensity (Fig.11) and the HfO_2 crystallization at the surface of the film (Fig.12). The excellent structural stability of HfSiON against crystallization and phase separation, and the resulting microscopic homogeneity are responsible for the stability of K-value even after 1000°C annealing (Fig.6.).

Compatibility with the poly-Si gate process and anomalous pMOS Vfb behavior

Fig.13 shows a cross-sectional TEM image of a poly-Si/HfSiON/Si stack after activation annealing (1100°C, 15 s). It was shown that the HfSiON remained amorphous even after annealing at 1100°C (Fig.13). The Hf concentration in the dielectric was depleted in the interfacial layer (Fig.13), while the TEM-EELS analysis revealed that the film contained a certain amount of N throughout the film. The stack showed excellent electrical behavior: nearly ideal Vfb values, negligible hysteresis, and low gate leakage (Fig.14). The gate leakage increased only by a factor of 1.5 at 85°C (Fig.14). Fig.15 shows the EOT vs. Jg relationship for n+poly-Si/HfSiON/Si stacks. The EOT was extracted at a surface electric field strength of 5 MV/cm [9]. The devices showed more than 1000 times reduction in leakage current relative to SiO_2 with an EOT of 17 to 20 Å, meeting the requirement for gate insulators for 45 nm Lg low-power MOS devices [3].

In the case of HfSiON, higher [N] leads to the suppression of B penetration (Fig.16). It has been reported that the penetration is closely related to the film structure[10]; the suppression of crystallization and phase separation achieved at [N] > 20at.% lead to the retardation of B diffusion through the film, resulting in our acceptable interface B concentration of $10^{17}cm^{-3}$.

Nearly ideal Vfb values were obtained for n+poly/HfSiON/p-Si capacitors irrespective of the Hf/Hf+Si ratio (Fig.17). However, for p+poly-Si devices, Vfb is shifted significantly in the negative direction as a result of positive charge creation. This anomalous pMOS Vfb behavior has also been reported in previous studies on Hf-based gate dielectrics [6,11]. Our experiments with varying Hf content revealed that a higher Hf led to an increase in this phenomenon (Fig.17), resulting in the speculation that positively charged defects were generated by the interaction between Hf and B diffused from the gate electrodes. Therefore some measures must be taken to prevent the penetration of B into the film before this film can be used in commercial LSIs.

Conclusion

The effects of the nitrogen in the HfSiON gate dielectric on the electrical and thermal properties were carefully investigated. It was clearly reported that the nitrogen in the HfSiON enhances the dielectric constant of the film. Microscopically homogeneous HfSiON films with a dielectric constant of more than 10 even after annealing at 1000°C were obtained for nitrogen concentrations of 20at.% or higher. Moreover, HfSiON was demonstrated to be well suited for the poly-Si gate process, except for the anomalous pMOS Vfb behavior. The experimental results of this study strongly suggest that HfSiON is the most probable material for first generation high-K gate dielectrics.

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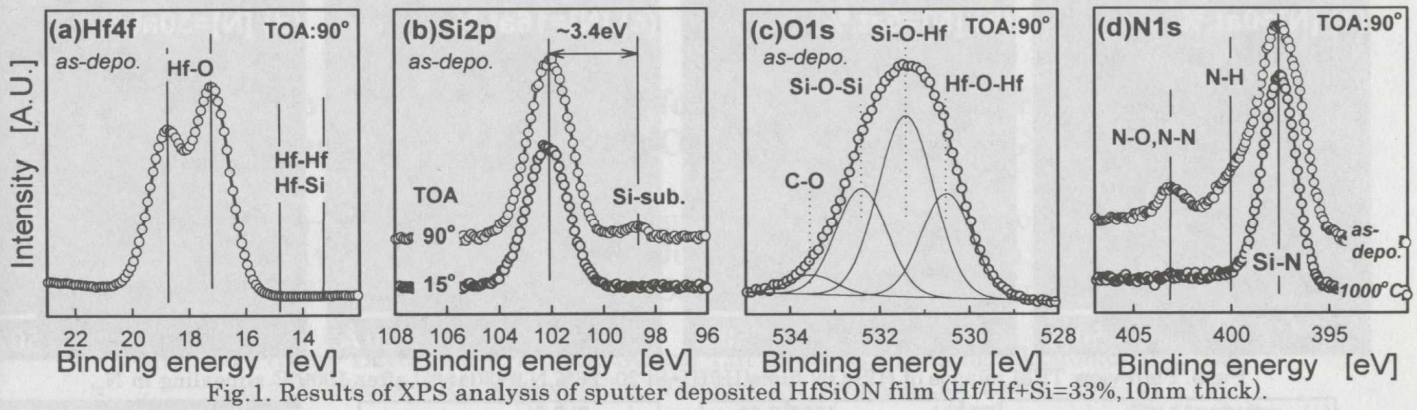


Fig.1. Results of XPS analysis of sputter deposited HfSiON film (Hf/Hf+Si=33%, 10nm thick).

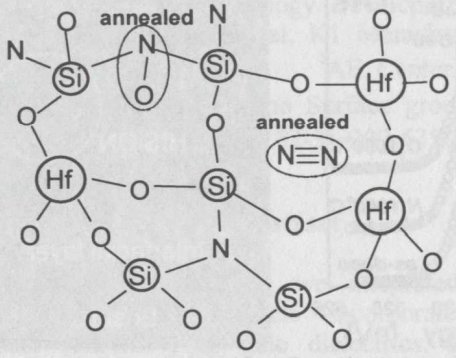


Fig.2. Schematic of bond configuration of HfSiON before annealing(assuming the coordination of 4 for Hf-O).

Table 1. Composition of HfSiON films measured by RBS.

[N]	Hf/Hf+Si (%)	N (at.%)
Low 5～6%	8	6
	22	5
Medium 13～16%	20	16
	35	13
High 23～30%	25	30
	33	29
	40	23

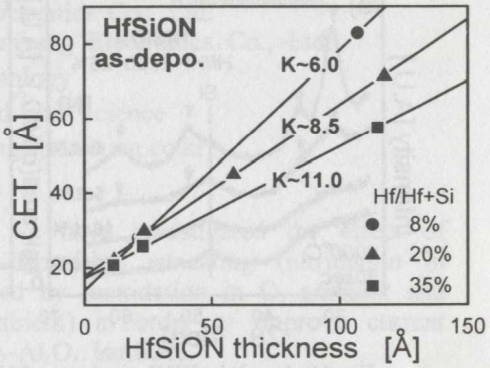


Fig.3. Evaluation of dielectric constant of HfSiON films.

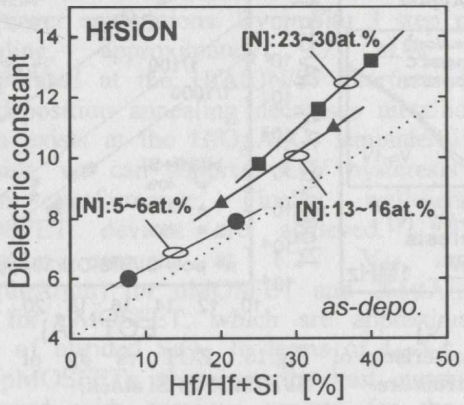


Fig.4. Dielectric constant of as-deposited HfSiON films listed in table 1.

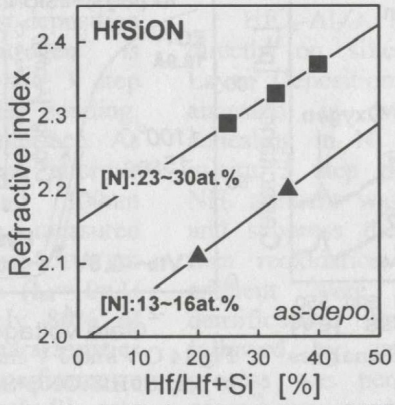


Fig.5. Refractive index of HfSiON films measured by ellipsometry.

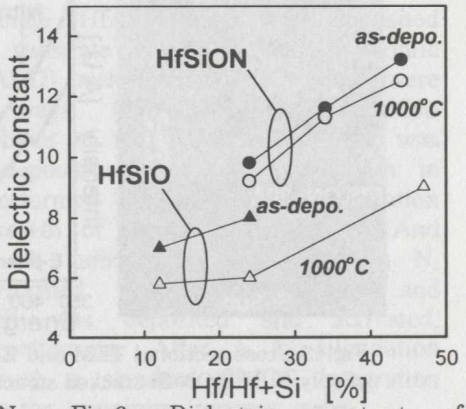


Fig.6. Dielectric constant of HfSiON films after 1000°C anneal.

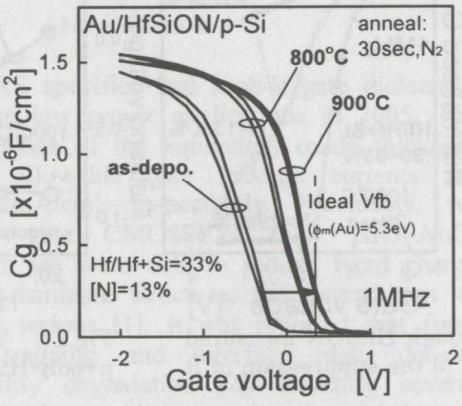


Fig.7 Improved CV characteristics of HfSiON by post deposition annealing.

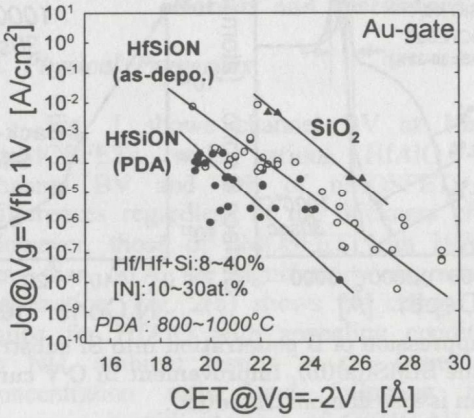


Fig.8. CET vs Jg relationship of HfSiON.

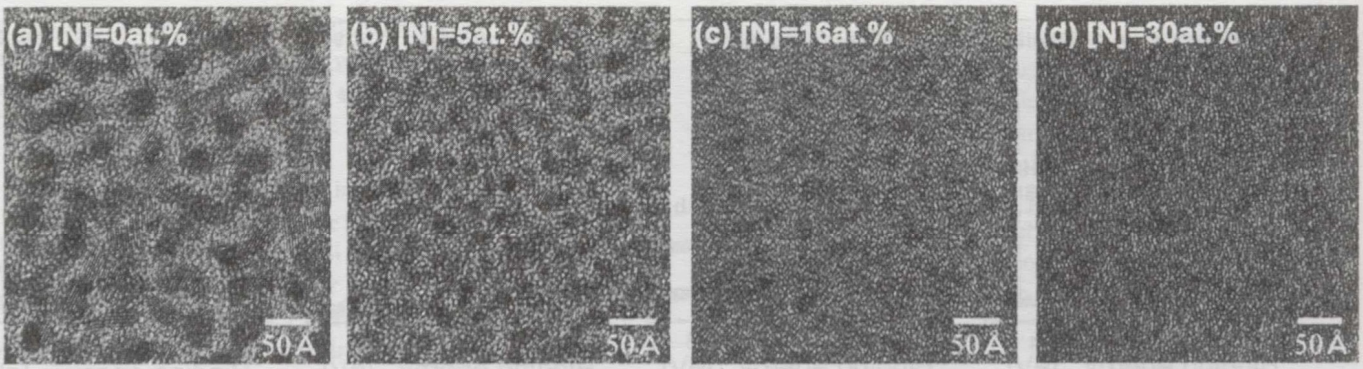


Fig.9. Plan-view TEM images of HfSiON films(Hf/Hf+Si:20~26%,N:0~30at.%) after 1000°C annealing in N_2.

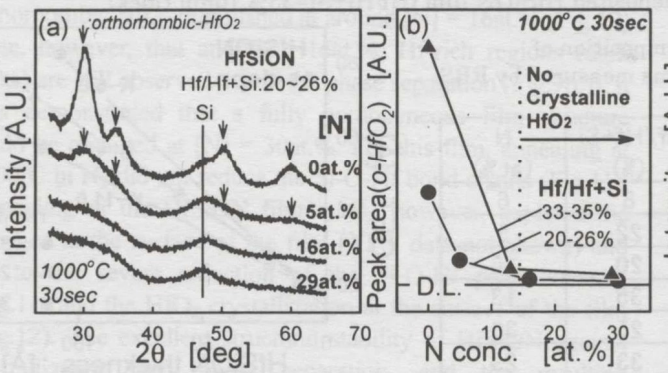


Fig.10. In-plain XRD analysis of HfSiON films after 1000°C annealing. N inhibits crystallization of the film.

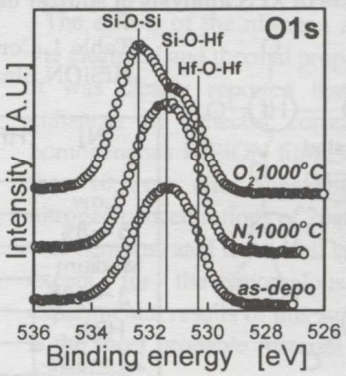


Fig.11. Chemical stability of Hf-O-Si bonds in HfSiON.

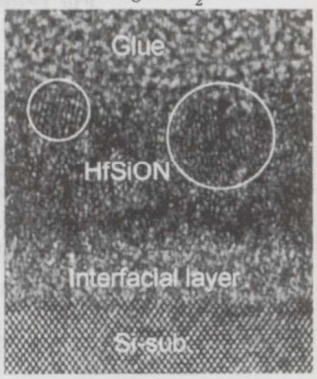


Fig.12. HfO_2 crystallization at HfSiON surface by O_2 anneal.

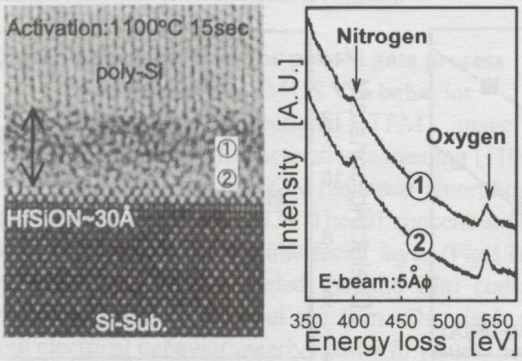


Fig.13 Cross-sectional TEM and EELS analyses of poly-Si/HfSiON/Si stacked structure

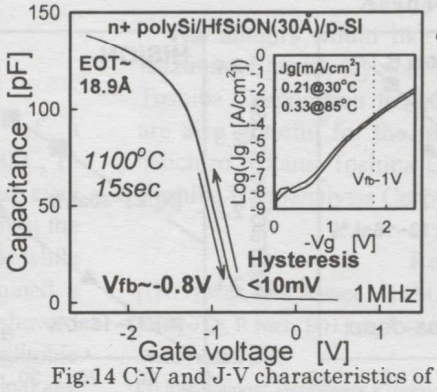


Fig.14 C-V and J-V characteristics of n+poly-Si/HfSiON/p-Si structure.

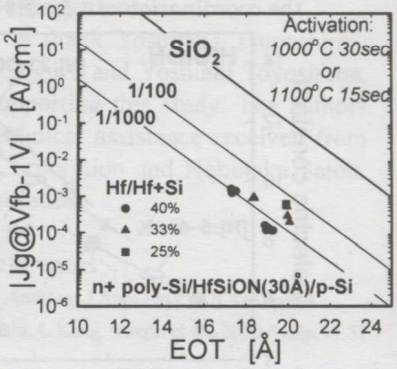
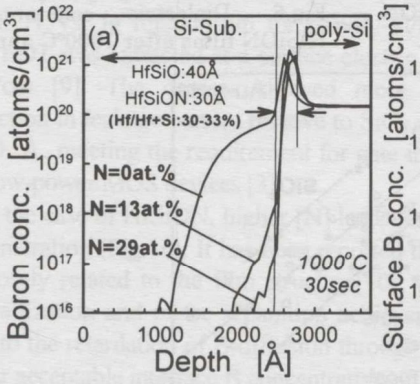
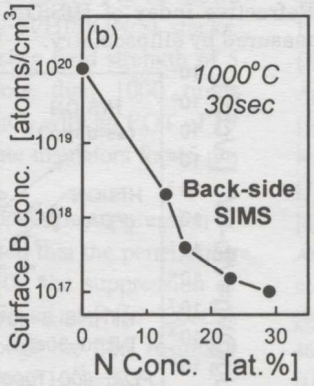


Fig.15. EOT vs Jg of n+poly-Si/HfSiON/p-Si stack.





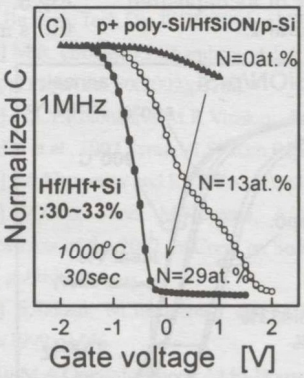


Fig.16. Suppression of B penetration into Si substrate through HfSiON measured by back-side SIMS((a)(b)). Improvement in C-V curve due to the suppression of B penetration is also demonstrated((c)).

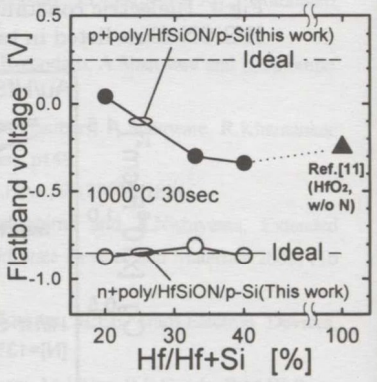


Fig.17. Vfb of n+poly and p+poly/HfSiON/p-Si structure.