東北大学 電気通信研究所

研究室外部評価資料

(2013 年度-2018 年度)

Activity Report of Research Laboratory for External Review

April 2013 - March 2019
(FY.2013-2018)

Research Institute of Electrical Communication

Tohoku University

ナノ集積デバイス・プロセス研究室

Nano-Integration Devices and Processing

A. 研究室名 / Research Laboratory

ナノ集積デバイス・プロセス研究室
Nano-Integration Devices and Processing

B. 構成員 / Faculty and Research Staff (as of May 1, 2019)

※ 欄を適宜追加削除等調整して下さい．期間内に異動等があった場合には，在籍期間を記載して下さい．

教授 / Professor	
氏名 Name	佐藤 茂雄 Shigeo Sato
分野名 Research Field	ナノ集積デバイス研究分野 Nano-Integration Devices
准教授 / Associate Professor	
氏名 Name	櫻庭 政夫 Masao Sakuraba
分野名 Research Field	量子ヘテロ構造高集積化プロセス研究分野 Group IV Quantum Heterointegration
助教 / Assistant Professor	
氏名 / Name	秋間 学尚 / Hisanao Akima (April 2013 – March 2018)
他 / Others	
	学術研究員: 1 名 (April 2019 -)

C. 研究目的 / Research Purpose

従来の高速性や大容量性に加え、低炭素社会実現へ向けた低消費電力性や災害時でも動作するロバスト性など多様な要求に対応できる次世代情報通信基盤技術の開発に向けて、3 次元ナノプロセス技術を駆使したシリコン系半導体デバイスの高機能・高性能化と、それらを用いた大規模集積回路の実現が重要な課題である。デバイスの高機能・高性能化においては、新材料や立体構造を導入した新トランジスタ素子・新メモリ素子の開発、量子効果など新しい原理によって動作する新原理動作デバイスの開発、これらに必要な 3 次元プロセス技術の開発を進める。併せて、3 次元集積化実装技術の開発、アナ・デジ混在ディペンダブル大規模集積回路の実現、非ノイマンアーキテクチャの実現に取り組む。

In addition to the conventional demands such as faster operation and larger throughput, low power operation for low-carbon emission and robust operation not damaged even in a disaster are required for the development of the next generation information technology. To meet these demands, studies on high functional and high performance Si-based semiconductor devices realized by 3-D nano-processing and large scale integration of such devices are important research subjects. We study the subjects such as new transistors and memories using new materials, new devices based on new principles like quantum effects, and required 3-D processing. Moreover, we develop advanced technologies related to 3-D nano-integration, dependable mixed signal LSI, and non von Neumann architecture.

D. 主な研究テーマ / Research Topics

1. 脳型計算ハードウェアに関する研究
2. 量子知能ハードウェアに関する研究
3. 脳型視覚情報処理システムに関する研究
4. 高度歪 IV 族半導体エピタキシャル成長のための低損傷基板非加熱プラズマ CVD プロセスに関する研究
5. IV 族半導体高度歪量子ヘテロ構造の高集積化プロセスに関する研究
6. IV 族半導体量子ヘテロナノデバイスの製作と高性能化に関する研究

1. Brain computing hardware
2. Intelligent quantum hardware

3. Brainmorphic visual information processing system
4. Low-damage plasma CVD process without substrate heating for epitaxial growth of highly strained group IV semiconductors
5. Large-scale integration process of group IV semiconductor quantum heterostructures
6. Fabrication of high-performance nanodevices utilizing group IV semiconductor quantum heterostructures

E. 学術論文等の編数 / The Number of Research Papers							
	2013	2014	2015	2016	2017	2018	Total
(1) 査読付学術論文 Refereed journal papers	1	5	3	3	5	3	20
(2) 原著論文と同等に扱う 査読付国際会議発表論文 Full papers in refereed conference proceedings equivalent to journal papers	0	0	0	0	0	0	0
(3) 査読付国際会議 Papers in refereed conference proceedings	7	5	3	6	10	7	38
(4) 査読なし国際会議・シンポジウム等 Papers in conference proceedings	6	5	10	9	9	7	46
(5) 総説・解説 Review articles	0	0	1	0	0	0	1
(6) 査読付国内会議 Refereed proceedings in domestic conferences	0	0	0	0	0	0	0
(7) 査読なし国内研究会・講演会 Proceedings in domestic conferences	5	5	6	7	11	5	39
(8) 著書 Books	1	0	0	0	1	0	2
(9) 特許 Patents	1	0	0	1	0	0	2
(10) 招待講演 Invited Talks	2	0	4	1	1	3	11

F. 特筆すべき研究成果 / Significant Research Achievements (FY.2013-2018)

See Ref. 1. "#" mark indicates research carried out at a former organization.

2013-2018 年度の研究成果（論文・特許など）のうち，前半（2013-2015 年度）と後半（2016-2018 年度）それぞれで代表的な数件（2-3 件程度ずつ）について，参考資料を引用して，その特徴と学術的意義などを簡単に紹介する．英文のみ，もしくは和文と英文で記載．
要約は 300 字程度．論文誌の要約/Abstract のコピー可．学術面での国際的インパクトならびに社会的影響を 100 字程度で記載．
必ずしも当該期間内に発表・出版したものに限るのではなく，例えば過去に発表したものでもこの期間内に成果が得られたり，評価されるようになったりしたものも含むものとする．
インパクトファクターや被引用件数など，できる限り第三者が定量的に評価できる指標を用いてアピールすること．それらの指標にはそぐわない場合には，その事情とそれに変わる適当な評価指標・尺度を示すこと．

[2013-2015]

1. N. Ueno, M. Sakuraba, S. Sato, J. Murota, "Epitaxial Growth of $Si_{1-x}Ge_x$ Alloys and Ge on Si(100) by Electron-Cyclotron-Resonance Ar Plasma Chemical Vapor Deposition without Substrate Heating", Thin Solid Films, vol. 557, pp. 31-35, 2014. Impact Factor: 1.939, Times Cited (Web of Science): 3

Abstract: By using electron-cyclotron-resonance (ECR) Ar-plasma chemical vapor deposition (CVD) without substrate heating, the epitaxial growth process of $Si_{1-x}Ge_x$ alloy and Ge films deposited directly on dilute-HF-treated Si(100) was investigated. From the reflection high energy electron diffraction patterns of the deposited $Si_{1-x}Ge_x$ alloy (x = 0.50, 0.75) and Ge films on Si(100), it is confirmed that epitaxial growth can be realized without substrate heating, and that crystallinity degradation at larger film thickness is observed. The X-ray diffraction peak of the epitaxial films reveals the existence of large compressive strain, which is induced by lattice matching with the Si(100) substrate at smaller film thicknesses, as well as strain relaxation behavior at larger film thicknesses.

International impact on both academic and social aspects: It is proposed that the ECR-plasma CVD process can be utilized for Ge fraction control in highly-strained heterostructure formation of group IV semiconductors. This indicates a possibility that thermal degradation problems at the semiconductor interfaces can be avoided, and will directly contribute to creation of higher-performance semiconductor devices in many electronic systems.

2. A. A. Shklyaev, V. I. Vdovin, V. A. Volodin, D. V. Gulyaev, A. S. Kozhukhov, M. Sakuraba, J. Murota, "Structure and optical properties of Si and SiGe layers grown on SiO_2 by chemical vapor deposition", Thin Solid Films, vol. 579, pp. 131-135, 2015. Impact Factor: 1.939, Times Cited (Web of Science): 10

Abstract: The properties of thin Si and SiGe layers grown on SiO_2 by chemical vapor deposition (CVD) were studied using transmission electron and atomic force microscopies, and Raman and photoluminescence (PL) spectroscopies. The layers with a composition of $Si_{0.5}Ge_{0.5}$ become composed of nanocrystals with an average size of about 100 nm at growth temperatures of 550 °C which is significantly lower than that for the pure Si layers. Moreover, the $Si_{0.5}Ge_{0.5}$ layers exhibit a broad PL peak centered at 0.8 eV, whereas the bandgap of unstrained $Si_{0.5}Ge_{0.5}$ is about 1 eV. This indicates that PL occurs through deep energy levels in the bandgap, which can be associated with crystal defects. The predominance of deep-level PL in radiative emission can be the result of a high concentration of defects that appear due to a low growth temperature.

International impact on both academic and social aspects: To fabricate optoelectronic devices, semiconductor materials must be optically transparent but enable the light emission in the telecommunication wavelength range of 1.3-1.6 μm. Si-based materials (such as $Si_{1-x}Ge_x$ for $x < 0.5$) can produce such emission through deep energy levels in its bandgap by induced crystal defects. This will directly contribute to integration of optoelectronic devices on Si integrated circuits in next-generation semiconductor electronics.

3. S. Sato, H. Akima, K. Nakajima, M. Sakuraba, “Izhikevich neuron circuit using stochastic logic”, Electron. Lett., vol. 50, pp. 1795-1797, 2014. Impact Factor: 1.232, Times Cited (Web of Science): 1

Abstract: A digital circuit of the Izhikevich neuron model using stochastic logic is proposed. Stochastic logic is employed in order to save the number of transistors required for multiplication operations. Successful operation of the proposed circuit has been confirmed.

International impact on both academic and social aspects: We successfully achieved a substantial saving of the number of transistors by employing stochastic logic. The compact digital circuit has good accuracy and reproduces the rich dynamics found in a biological brain. It could be widely used for brain computer and brain machine interface.

[2016-2018]

1. W. A. Borders, H. Akima, S. Fukami, S. Moriya, S. Kurihara, Y. Horio, S. Sato, H. Ohno, “Analogue spin-orbit torque device for artificial-neural-network-based associative memory operation”, Appl. Phys. Express, vol. 10, no. 1, p. 013007 (4 pages), 2017. Impact Factor: 2.555, Times Cited (Web of Science): 44

Abstract: We demonstrate associative memory operations reminiscent of the brain using nonvolatile spintronics devices. Antiferromagnet-ferromagnet bilayer-based Hall devices, which show analogue-like spin-orbit torque switching under zero magnetic fields and behave as artificial synapses, are used. An artificial neural network is used to associate memorized patterns from their noisy versions. We develop a network consisting of a field-programmable gate array and 36 spin-orbit torque devices. An effect of learning on associative memory operations is successfully confirmed for several 3 x 3-block patterns. A discussion on the present approach for realizing spintronics-based artificial intelligence is given.

International impact on both academic and social aspects: A nonvolatile analog memory is an indispensable device for efficient circuit implementation of neural networks. Our results indicate that we can make a compact and low-power analog LSI by employing this spintronics device, and thus accelerate the development of AI hardware. The paper has been selected as one of the 41st JSAP outstanding papers.

2. M. Sakuraba, K. Sugawara, T. Nosaka, H. Akima, S. Sato, “Carrier properties of B atomic-layer-doped Si films grown by ECR Ar plasma-enhanced CVD without substrate heating”, Sci. Technol. Adv. Mat., vol. 18, pp. 294-306, 2017. Impact Factor: 4.787, Times Cited (Web of Science): 1

Abstract: B atomic-layer-doped Si films were formed on Si(100) by B atomic layer (AL) formation followed by Si cap layer deposition in low-energy Ar plasma-enhanced chemical-vapor deposition without substrate heating. After fabrication of Hall-effect devices with the B AL-doped Si films on unstrained and 0.8%-tensile-strained Si(100)-on-insulator substrates (maximum process temperature 350°C), carrier properties were electrically measured at room temperature. Typically for the initial B amount of 2×10^{14} cm^{-2} and 7×10^{14} cm^{-2}, B concentration depth profiles showed a clear decay slope as steep as 1.3 nm/decade. Dominant carrier was a hole and the maximum sheet carrier densities as high as 4×10^{13} cm^{-2} and 2×10^{13} cm^{-2} (electrical activity ratio of about 7% and 3.5%) were measured respectively for the unstrained and 0.8%-tensile-strained Si with Hall mobility around 10–13 $cm^2 V^{-1} s^{-1}$. Moreover, mobility degradation was not observed even when sheet carrier density was increased by heat treatment

at 500–700 °C.

International impact on both academic and social aspects: The atomic-layer doping technique in epitaxy has been attracted attention as a low-resistive ultrathin semiconductor film as well as a two-dimensional carrier transport system. There is a possibility that the local carrier (ionized B atom) concentration around the B AL in Si reaches around 10^{21} cm^{-3} and 2-D impurity-band formation with strong Coulomb interaction is expected. This will directly contribute to creation of higher-performance semiconductor devices in many electronic systems.

3. H. Yamamoto, S. Moriya, K. Ide, T. Hayakawa, H. Akima, S. Sato, S. Kubota, T. Tanii, M. Niwano, S. Teller, J. Soriano, A. Hirano-Iwata, "Impact of modular organization on dynamical richness in cortical networks," Sci. Adv., vol. 4, p. eaau4914 (11 pages), 2018. Impact Factor: 12.804, Times Cited (Web of Science): 4

Abstract: As in many naturally formed networks, the brain exhibits an inherent modular architecture that is the basis of its rich operability, robustness, and integration-segregation capacity. However, the mechanisms that allow spatially segregated neuronal assemblies to swiftly change from localized to global activity remain unclear. Here, we integrate microfabrication technology with in vitro cortical networks to investigate the dynamical repertoire and functional traits of four interconnected neuronal modules. We show that the coupling among modules is central. The highest dynamical richness of the network emerges at a critical connectivity at the verge of physical disconnection. Stronger coupling leads to a persistently coherent activity among the modules, while weaker coupling precipitates the activity to be localized solely within the modules. An in silico modeling of the experiments reveals that the advent of coherence is mediated by a trade-off between connectivity and subquorum firing, a mechanism flexible enough to allow for the coexistence of both segregated and integrated activities. Our results unveil a new functional advantage of modular organization in complex networks of nonlinear units.

International impact on both academic and social aspects: We have developed a neuroengineering tool for designing neuronal circuits in vitro that mimic the integration-segregation capacity of the brain. This study shows the potential of in vitro tools and biophysical models to progress in the understanding of collective phenomena in such a fascinating and rich complex system like the brain. Also, our findings about collective behavior related to modular structure will be utilized in making a neural network LSI.

G. 特筆すべき活動 / Significant Activities (FY.2013-2018)

See Ref. 2-9. "#" mark indicates research carried out at a former organization.

研究室外部評価参考資料の 2 以降を参照しながら，2013-2018 年度のなどの活動の中から特筆すべきものを取り出し，前半（2013-2015 年度）と後半（2016-2018 年度）に分けて簡単に紹介する．英文のみ，もしくは和文と英文で記載．

[2013-2015]

1. Activities in academic societies (Selected)

Shigeo Sato

- Director of Japanese Neural Network Society (2013-2015)
- Action Editor of Neural Networks (2013-2015)
- Associate Editor of the journal NOLTA, IEICE (2013-2015)
- Program Committee Member of International Joint Conference on Neural Networks (IJCNN) (2014)
- Student Activities Committee Member of IEEE Sendai Section (2014-2015)
- Vice Chair of Technical Committee on Neurocomputing (NC), IEICE (2015)

Masao Sakuraba

- Executive Secretary of ULSI Device Research Committee, Si Technology Division, The Japan Society of Applied Physics (2014-2015)
- Member of Paper Award Committee, The Japan Society of Applied Physics (2013-2014)

2. Contributions to society (Selected)

Shigeo Sato

- Part-Time Lecturer at National Institute of Technology, Sendai College (2013)

Masao Sakuraba

- Part-Time Lecturer at National Institute of Technology, Sendai College (2013-2015)

3. Research funds/grants received (Selected)

Shigeo Sato

- Grant-in-Aid for Scientific Research (C), "Development of a nanosized synapse device for brain computers", Principal Investigator S. Sato, Co-Investigator M. Sakuraba, Total Budget 3,600,000 Yen, Research Project Number 25330279, Japan Society for the Promotion of Science. (2013-2015)

Masao Sakuraba

- Grant-in-Aid for Scientific Research (B), "Process Development for High-Performance Highly-Strained Quantum-Heterostructure Resonant-Tunneling Devices of Group-IV Semiconductors", Principal Investigator M. Sakuraba, Total Budget 15,700,000 Yen, Research Project Number 23360003, Japan Society for the Promotion of Science.(2011-2013)

4. International joint research, collaborative research, and collaborative education (Selected)

Shigeo Sato

- Research Collaboration with Prof. Madrenas in 2015 as the guest professor about hardware implementation of neural networks.

Masao Sakuraba

- Research Collaboration with Prof. Tillack in 2013-2015 about C and Si delta doping in Ge epitaxial growth.

5. Honors, awards, and prizes (Selected)

Masao Sakuraba

- Research Encouragement Award, Minoru Ishida Foundation (Japan), "Plasma CVD Processing for Quantum Heterointegration of Group IV Semiconductors", November 27, 2015 (http://www.ishida-kinenzaidan.or.jp/)

Students

- 2015 IEICE Academic Encouragement Award, S. Moriya, “LSI Design of a Neural Network Model for Detecting Local Image Motion by Motion Stereo Vision”
- IEEE Sendai Section Student Awards 2015 (The Best Paper Prize), Y. Osakabe, “Superconductivity Coherence in Series Array of Nb/AlO_x/Nb Josephson Junctions”

[2016-2018]

1. Activities in academic societies (Selected)

Shigeo Sato

- Director of Japanese Neural Network Society (2016-2018)
- Action Editor of Neural Networks (2016-2018)
- Associate Editor of the journal NOLTA, IEICE (2016-2018)
- Chair of Technical Committee on Neurocomputing (NC), IEICE (2016)
- Program Committee Member of International Conference on Neural Information Processing (ICONIP) (2016-2017)
- Program Committee Member of International Symposium on Superconductivity (ISS) (2016-2018)
- Technical Program Committee Member of IEEE HISTELCON (HISTory of ELectrotechnology CONference) 2017

Masao Sakuraba

- Executive Secretary of ULSI Device Research Committee, Si Technology Division, The Japan Society of Applied Physics (2016-2018)

2. Contributions to society (Selected)

Shigeo Sato

- Part-Time Lecturer at National Institute of Technology, Hachinohe College (2016-2018)

Masao Sakuraba

- Part-Time Lecturer at National Institute of Technology, Sendai College (2016-2018)

3. Research funds/grants received (Selected)

Shigeo Sato

- Grant-in-Aid for Challenging Research (Exploratory), "Learning of neuromorphic quantum computation algorithms towards its hardware implementation", Principal Investigator S. Sato, Total Budget 4,700,000 Yen, Research Project Number 17K18864, Japan Society for the Promotion of Science. (2017-2018)
- Japan Science and Technology Agency CREST (A survey on a particular subject), "Study on system application of spintronics devices", Principal Investigator S. Sato, Total Budget 3,000,000 Yen (2018)
- Collaborative research with Sumitomo Metal Mining about SiC devices, Principal Investigator S. Sato, Co-Investigator M. Sakuraba, Total Budget 9,030,000 Yen (2018-2019)

Masao Sakuraba

- Grant-in-Aid for Challenging Research (Exploratory), "Experimental Research on Crystal Structure Transformation by Low-Energy Plasma Induced Reconstruction in Si Ultrathin Film", Principal Investigator M. Sakuraba, Co-Investigator S. Sato, Total Budget 4,900,000 Yen, Research Project Number 18K18987, Japan Society for the Promotion of Science. (2018-2019)

6. Honors, awards, and prizes (Selected)

Shigeo Sato

- APEX 10th Anniversary Collection
  W. A. Borders, H. Akima, S. Fukami, S. Moriya, S. Kurihara, Y. Horio, S. Sato, H. Ohno, "Analogue spin-orbit torque device for artificial-neural-network-based associative memory operation", Appl. Phys. Express, vol. 10, no. 1, p. 013007 (4 pages), 2017. (Dec. 20, 2016)

Students

- IEEE Computational Intelligence Society (CIS) Young Researcher Award (YRA) 2018, S. Kurihara, "Visual processing system for spatial perception based on motion stereo vision"