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

固体電子工学研究室

Solid State Electronics

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

A. 研究室名 / Research Laboratory

固体電子工学研究室
Solid State Electronics

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	末光　眞希 Maki Suemitsu (April 2008-March 2018) 佐藤　茂雄（兼） Shigeo Sato (April 2018 -)
分野名 Research Field	固体電子工学研究分野 Solid State Electronics

准教授 / Associate Professor

氏名 Name	吹留　博一 Hirokazu Fukidome (April 2012-)
分野名 Research Field	固体電子物性工学研究分野 Solid State Physics for Electronics

助教 / Assistant Professor

氏名 / Name	

他 / Others

- 学術研究員: 2 名
- 日本学術振興会特別研究員 PD: 2 名
- 日本学術振興会特別研究員 DC: 2 名
- 日本学術振興会海外特別研究員: 1 名

- Research Fellow: 1 person
- Japan Society for the Promotion of Science Fellows (Postdoctoral fellow): 2 persons
- Japan Society for the Promotion of Science Fellows (Doctoral Course): 2 persons
- Japan Society for the Promotion of Science Overseas Fellows: 2 persons

C. 研究目的 / Research Purpose

少子高齢化が加速する日本の持続成長に不可欠な超スマート社会実現に貢献することを目的として，次世代超高速，省エネルギー素子技術を開拓・実用化するために，SiC、グラフェン，その他の二次元電子系などの材料創製，精密物性評価，デバイス・回路までをカバーする統合的研究を精力的に推進している．

For realizing smart society vital for sustainable growth of Japan where low birthrate and population aging, our research group aims at realization of next-generation ultrahigh-speed as well as energy-saving device. For this purpose, we strenuously advance the integrated research from materials exploration and creation, precise electronic properties characterization to device and circuit developments.

D. 主な研究テーマ / Research Topics

1. Si(110)表面反応の動的挙動の研究
2. 大気圧プラズマによる Si 系薄膜形成と薄膜トランジスタへの応用
3. Si 基板上 SiC 薄膜成長の表面化学の研究
4. グラフェン･オン･シリコン構造とその超高速デバイスへの応用

5. MEMS 技術を援用した Dirac 電子系の新機能開拓と多機能集積デバイス開発
6. オペランド顕微分光法の開発とそれを用いた新奇なナノデバイス物理の開拓

1. Kinetic study of surface chemical reactions on Si(110)
2. Formation of Si and Si-related films by use of normal-pressure plasma-enhanced chemical vapor deposition.
3. Surface chemistry during growth of SiC thin films on Si substrates.
4. Formation of epitaxial graphene on Si and its applications to ultrahigh-speed devices.
5. Development of novel functionalities of Dirac electrons by use of MEMS-assisted nanofabrication of substrates.
6. Development of operando spectromicroscopy and its application to exploration of novel nanodevice physics

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	16	7	8	11	7	5	54
(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	3	0	11	5	0	0	19
(4) 査読なし国際会議・シンポジウム等 Papers in conference proceedings	11	6	4	5	6	1	33
(5) 総説・解説 Review articles	3	3	1	1	0	0	4
(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	20	15	10	20	8	5	78
(8) 著書 Books	1	0	2	0	0	1	4
(9) 特許 Patents	3	3	4	9	4	0	23
(10) 招待講演 Invited Talks	10	13	9	14	3	5	54

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.
<u>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.</u>
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]

In this period, we established the world’s highest level graphene growth method on SiC thin films on Si substrates, and succeeded in three-dimensionally controlling band structures of graphene at a nanoscale, and fabricating graphene field-effect transistor that demonstrated one of the highest high-frequency characteristics.

1. M. Suemitsu, and H. Fukidome, "Epitaxial Graphene on Silicon Substrates," J. Phys. D, Vol. 43, No. 37, pp. 374012-1-11, 2010. [IF: 2.829], [Times Cited: 86 (53 from 2013)]

Abstract: By forming an ultrathin (~100 nm) SiC film on Si substrates and by annealing it at ~1500K *in vacuo*, few-layer graphene is formed on Si substrates. Graphene grows on three major low-index surfaces: (1 1 1), (1 0 0) and (1 1 0), allowing us to tune its electronic properties by controlling the crystallographic orientation of the substrate. This *graphene on silicon* (GOS) technology thus paves the way to industrialization of this new material with inherent excellence. With its feasibility in Si technology, GOS is one of the most promising candidates as a material for *Beyond CMOS* technology.

International impact on both academic and social aspects: The pioneering achievement on the fusion of graphene with Si-based electronics by realizing the graphene growth on the SiC thin films on the Si substrates (GOS). This paper is still cited because it is currently like a textbook on the high-quality growth, surface and interface electronic properties, and device applications of GOS.

This GOS technology will give a great impact on industries because this technology is the basis of graphene-based Beyond CMOS fusing with Si electronics.

2. M.-H. Jung†, G.-H. Park, T. Yoshida, H. Fukidome, T. Suemitsu, T. Otsuji, and M. Suemitsu, " High-Performance Graphene Field-effect Transistors with Extremely Small Access Length using Self-Aligned Source and Drain Technique," Proceedings of the IEEE, 101. (2013), pp.1603-1608. [IF: 10.694], [Times Cited: 11]

Abstract: Self-aligned source/drain (S/D) graphene field-effect transistors (GFETs) with extremely small access lengths were successfully fabricated using a simple device fabrication process without sidewall spacer formation. The self-aligned S/D GFET exhibits superior electrical characteristics, such as the intrinsic carrier mobility of 6100 cm^2/Vs. In particular, a cutoff frequency (f_T) of 13 GHz was achieved with a rather large gate length (L_G = 3 μm). The high-frequency characteristics ($f_T \cdot L_G$ = 0.04 THz·μm) was the highest record as of 2013. Our result demonstrates the promising future of this self-aligned GFET.

International impact on both academic and social aspects: The pioneering achievement demonstrating the intrinsic capability of graphene for radio-frequency (RF) electronics. This achievement was realized by minimizing the contribution of parasitic regions, except the graphene channel region, with the techniques that we developed by using wet etching of SiO_2 with hydrofluoric acid.

The great impact on industries is evidenced by industrial-academia collaborations with Sumitomo Electric Industries and ShinEtsu Chemicals, which were partially supported by NEDO from the Ministry of Economy, trade, and industry.

3. H. Fukidome, T. Ide, Y. Kawai, T. Shinohara, N. Nagamura, K. Horiba, M. Kotsugi,T. Ohkochi, T. Kinoshita, H. Kumigashira, M. Oshima, and M. Suemitsu, " Microscopically-Tuned Band Structure of Epitaxial Graphene through Interface and Stacking Variations Using Si Substrate Microfabrication," Scientific Reports, Vol. 4, pp. 5173-1-6, 2014. [IF: 4.122], [Times Cited: 6]

Abstract: Graphene exhibits unusual electronic properties, caused by a linear band structure near the Dirac point. This band structure is determined by the stacking sequence in graphene multilayers. Here we present a novel method of microscopically controlling the band structure. This is achieved by epitaxy of graphene on 3C-SiC(111) and 3C-SiC(100) thin films grown on a 3D microfabricated Si(100) substrate (3D-GOS (graphene on silicon)) by anisotropic etching, which produces Si(111) microfacets as well as major Si(100) microterraces. We show that tuning of the interface between the graphene and the 3C-SiC microfacets enables microscopic control of stacking and ultimately of the band structure of 3D-GOS, which is typified by the selective emergence of semiconducting and metallic behaviours on the (111) and (100) portions, respectively. The use of 3D-GOS is thus effective in microscopically unlocking various potentials of graphene depending on the application target, such as electronic or photonic devices.
International impact on both academic and social aspects: The pioneering achievement of three-dimensionally controlling structural and electronic properties of graphene by fusing with Micro Electro Mechanical System (MEMS). This was enabled by spatially controlling the epitaxy of graphene SiC thin films through microstructuring Si substrates using MEMS.

This technology will enable to nanoscale integration of electronic (e.g. RF transistors) and photonic (e.g. lasers) devices operating at terahertz (THz) frequencies. These integrated THz devices will be core technologies for the more advanced wireless communication system (Beyond 6G).

[2016-2018]

In addition to graphene material and device reasearches at the world's highest level, we have newly developed operando spectrosmicroscopy enabling electronic states of surface and interfaces of device, which determine carrier transport properties and device performances, during device operation.

1. H. Fukidome, M. Kotsugi, K. Nagashio, R. Sato, T. Ohkouchi, T. Itoh, A. Toriumi, M. Suemitsu, and T. Kinoshita, " Microscopically-Tuned Band Structure of Epitaxial Graphene through Interface and Stacking Variations Using Si Substrate Microfabrication," Scientific Reports, Vol. 4, pp. 3713-1-5, 2014. [IF: 4.122], [Times Cited: 11]

Abstract: Graphene, a 2D crystal bonded by π and σ orbitals, possesses excellent electronic properties that are promising for next-generation optoelectronic device applications. For these a precise understanding of quasiparticle behavior near the Dirac point (DP) is indispensable because the vanishing density of states (DOS) near the DP enhances many-body effects, such as excitonic effects and the Anderson orthogonality catastrophe

(AOC) which occur through the interactions of many conduction electrons with holes. These effects renormalize band dispersion and DOS, and therefore affect device performance. For this reason, we have studied the impact of the excitonic effects and the AOC on graphene device performance by using X-ray absorption spectromicroscopy on an actual graphene transistor in operation. Our work shows that the excitonic effect and the AOC are tunable by gate bias or metal contacts, both of which alter the Fermi energy, and are orbital-specific.
International impact on both academic and social aspects: The pioneering achievement of tuning the relativistic quantum effects (RQEs), such as the excitonic effect and the AOC by the field-effect. We demonstrated that we tune RQEs at a nanoscale this way.

This work gives an impact on the industrial applications for the next-generation communication, such as graphene field-effect transistor (GFET) for THz utilization. This is because we can designate the adequate device fabrication process of high-performance GFET, based on the observation of the electronic-state changes at the interface between graphene and metal electrodes, which is the determining factor in device performances, was element-specifically visualized at a nanoscale.

2. K. Omika, Y. Tateno, T. Kouchi, T. Komatani, S. Yaegassi, K. Yui, K. Nakata, N. Nagamura, M. Kotsugi, K. Horiba, M. Oshima, M. Suemitsu, and H. Fukidome, " Operation Mechanism of GaN-based Transistors Elucidated by Element-Specific X-ray Nanospectroscopy," Scientific Reports, Vol. 8, pp. 13268-1-9, 2018. [IF: 4.122], [Times Cited: 1]

Abstract: With the rapid depletion of communication-frequency resources, mainly due to the explosive spread of information communication devices for the internet of things, GaN-based high-frequency high-power transistors (GaN-HEMTs) have attracted considerable interest as one of the key devices that can operate in the high-frequency millimeter-wave band. However, GaN-HEMT operation is destabilized by current collapse phenomena arising from surface electron trapping (SET), which has not been fully understood thus far. Here, we conduct quantitative mechanistic studies on SET in GaN-HEMTs by applying element- and site-specific photoelectron nanospectroscopy to a GaN-HEMT device under operation. Our study reveals that SET is induced by a large local electric field. Furthermore, surface passivation using a SiN thin film is demonstrated to play a dual role: electric-field weakening and giving rise to chemical interactions that suppress SET. Our findings can contribute to the realization of high-capacity wireless communication systems based on GaN-HEMTs.
International impact on both academic and social aspects: The pioneering achievement of quantitatively measuring charge transfer of surface states with a high precision of $\sim 10^{11}$ cm^{-2} and a spatial resolution of 70 nm. By utilizing the charge balance between the surface state charge density and the charged density in the channel, this work enables to measure the electronic states of the buried channel layer that has never be observed by photoelectron spectroscopy.

This work contributes to 5G on the stabilization of the 5G wireless network. GaN-HEMT is used for the base stations for 5G. The operation of GaN-HEMT is made destabilized by the carrier trapping of surface states, which is called current collapse phenomena. Our work is useful for taking measures for the suppression of the current collapse phenomena.

3. K.-S. Kim, G.-H. Park, H. Fukidome, T. Someya, T. Iimori, F. Komori, I. Matsuda, and M. Suemitsu, "A table-top formation of bilayer quasi-free-standing epitaxial graphene on SiC(0001) by microwave annealing in air," Carbon, Vol. 130, pp. 792-798, 2014. [IF: 7.466], [Times Cited: 0]

Abstract: We propose an ultrafast synthesis method to obtain quasi-free-standing bilayer epitaxial-graphene (QFSEG) on SiC(0001). By applying a microwave annealing (MWA) in air to a monolayer epitaxial graphene (EG) grown on SiC(0001), the EG's ($6\sqrt{3} \times 6\sqrt{3}$) R30° reconstructed buffer layer is decoupled from the SiC substrate and becomes the second graphene layer. Oxidation of the SiC surface is suggested as the most likely mechanism of the decoupling, and the electrical properties of this MWA-QFSEG are actually quite similar to those of the QFSEGs formed by conventional annealing in air. The process time has however been reduced by more than one order of magnitude, which will surely contribute to the betterment of the productivity of the EG-based devices.

International impact on both academic and social aspects：The pioneering achievement of controlling graphene/SiC interface by the use of microwave chemistry. This method improves carrier transport properties drastically.

The method using microwave is affordable, so that this method is appropriate for commercial fabrication process of GFET. In this respect, out work can give an impact on beyond 6G.

※ In the period of 2013-2018, we created the world’s highest level of materials growth and device fabrication of graphene and other 2D electron systems, and furthermore operando spectromicroscopy that bridges the gap between materials electronic properties and device performances. Thus, we realized science-based device Research & Development system with the academia-industry-government alliance.

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**

(1) Activities on committees of academic societies

(Suemitsu)

・ Chief of Tohoku chapter of Japan Society of Applied Physics (2014-2016), for managing the Tohoku chapter.

(Fukidome)

・ Executive secretary of surface and thin film division of Japanese Society of Applied Physics (2015-2017), for management of the surface and thin film division.

(2) Planning and organizing academic international conferences.

(Fukidome)

・ Program Committee of MNC2013 (2013), for program editing of International Microprocesses and Nanotechnology Conference 2013.

・ Program Committee of IEEE NEMS (2015-2016), for program editing of the International conference of Nano Electro Mechanical System and Nanotechnology.

(3) Editor and reviewer for academic journals.

(Suemitsu)

・ Proc. IEEE (flagship journal in electrical, electronics, and information engineering) Guest editor (2013), for the editing the special issue of graphene growth and device application.

(Fukidome)

・ Associate editor of Scientific Reports (Nature Publishing Group) (2014-2017), in charge of materials science and electronics

2. **Contributions to society**

(1) Educational activities outside university

・ School visit at Seiryo high school (2013), for giving a lecture of electronics.

(2) Instruction and education for industry

(Suemitsu and Fukidome)

・ The instruction of graphene epitaxy and fabrication of field-effect transistors using epitaxial graphene as channels (2014-218), for Sumitomo Electric Industries

3. **Research funds/grants received**

(1) Grant-in-Aid for Scientific Research (KAKENHI)

(Suemitsu)

Principal Investigator:

- Scientific Research (B) for epitaxial growth of graphene on Si substrate (2013-2015)

Co-investigator:

- Specially promoted research (co-investigator) about creation of graphene terahertz lasers (2013-2017)

(Fukidome)

- Scientific Research (B) for developing operando spectromicroscopy to bridge a gap between material properties and device performances (2015-2017)

(2) Other grants and subsidies

(Suemitsu and Fukidome)

- NEDO national project from the Ministry of Economy, trade, and industry for commercialization of graphene field-effect transistors (2014-2016), as co-investigators

(Suemitsu)

- Contract research expenses from Sumitomo Electric Industries for graphene synthesis and device applications, as the principal investigator (2013-2017)

(Fukidome)

- Contract research expenses from ShinEtsu Chemicals for graphene synthesis on hybrid wafers, as the principal investigator (2013-2016)

4. International joint research, collaborative research, and collaborative education

- Collaboration with Prof. Filimonov from 2013 to 2015 as the guest professor about kinematic study on the epitaxy of SiC thin film on Si substrate.
- Collaboration with Dr. Karsten Horn at Fritz-Haber Institute in 2014 as the guest professor at our Laboratory.

5. Achievements of work done under the framework of Joint Usage/Research Center

- The supercleanroom of Laboratory for Nanoelectronics and Spintronics for the joint usage was used for the instruction of graphene-based FET to Sumitomo Electric Industries. This led to the NEDO national project with Sumitomo Electric Industries.
- Based on RIEC cooperation projects by Suemitsu and Fukidome, our graphene growth and device fabrication has been greatly improved and constructed collaborations. As a result, we received grants as industry-academia alliances;

  - Contract research expenses from Sumitomo Electric Industries

  - Contract research expenses from ShinEstu Chemicals
- 7 patents have been submitted with Sumitomo Electric Industries

6. Research supervision

- Our laboratory made efforts for the education for foreign students, such as doctoral degrees of 2 students from South Korea, as well as students from Japan.

7. **Honors, awards, and prizes**

- M. Ishida Research Encouragement Award for development of operando x-ray spectromicroscopy and its application to 2D electron devices (2015) (Fukidome)

8. **Others**

- Our laboratory actively sent out research achievements by using newspaper (8 pieces), such as Nikkei Newspaper.

- Director of alumni association of Tohoku University (2008-2018)

[2016-2018]

1. **Activities in academic societies**

(1) Activities on committees of academic societies

(Suemitsu)

- Fellow of Japan Society of Applied Physics (2017), for contribution of his research on SiC and graphene, and management of the society.

(Fukidome)

- Executive secretary of surface and thin film division of Japanese Society of Applied Physics (2015-2017), for management of the surface and thin film division.

(2) Planning and organizing academic international conferences.

- Vice chair of Local Committee of ASCIN 2018 (2017-2018), for the management of ACSIN 2018 held at Sendai (Fukidome)

(3) Editor and reviewer for academic journals.

- Associate editor of Scientific Reports (Nature Publishing Group) (2014-2017), in charge of materials science and electronics

2. **Contributions to society**

- Instruction of graphene epitaxial growth to ShinEstu chemicals.

- Instruction of graphene epitaxial growth and device applications to Sumitomo Electric Industries

3. **Research funds/grants received**

(1) Grant-in-Aid for Scientific Research (KAKENHI)

- Challenging Research (Exploratory) (Principal Investigator: Fukidome) (2018-2019), for quantum biological study using operando soft x-ray time-resolved spectroscopy.
  Challenging Research (Exploratory)

- Scientific Research (S) (Principal Investigator: Prof. Otsuji, Co-investigator: Fukidome) (2016-

2020), for stacked growth of 2D materials and its device application.

(2) Other grants and subsidies

- SCOPE national project from Ministry of Internal affairs and Communication with the alliance between RIEC and (NICT) (Principal-investigator: Fukidome) (2018). In 2018, this project kicked off as Phase I for one year. At the end of the year end of 2018, this project was reviewed and highly appreciated (within Top 30%). Then, our SCOPE project Phase I was decided to continue as SCOPE project Phase II in 2019-2020.

4. International joint research, collaborative research, and collaborative education

- Collaboration with Prof. Filimonov from 2016 to 2017 as the guest professor about kinematic study on the epitaxy of SiC thin film on Si substrate.

5. Achievements of work done under the framework of Joint Usage/Research Center

- Through the RIEC collaboration project (2016-2018) which Fukidome operated for the device study using operando spectromicroscopy, we succeeded in making the industrial-academia-government alliance between RIEC, Sumitomo Electric Industries, and National Institute of Information, Communication and Technology (NICT). This project led to the national SCOPE project from the Ministry of Economy, Trade, and Industry (Principal Investigator: Fukidome, Co-investigator: Dr. Watanabe of NICT).

- 15 patents have been submitted with Sumitomo Electric Industries

6. Research supervision

- Our laboratory made efforts for the education for foreign students, such as doctoral degrees of 1 student from South Korea, as well as students from Japan.

7. Honors, awards, and prizes

(Suemitsu)

- IAAM medal from International Association of Advanced Materials Medal (IAAM medal) for the year 2016, for his study on SiC and graphene growth.

(Fukidome)

- RIEC Award for 2D electron device researches and developments by using x-ray operando spectromicroscopy (2016)

8. Others

- Fukidome cooperated the promotion of installing the next-generation highly-brilliant soft x-ray source facility that has been decided to be constructed in the campus of Tohoku University in 2023, by submitting the proposal of the beamline and playing a role as a member of the committee for the next-generation soft x-ray source facility.

・ Director of alumni association of Tohoku University (2008-2018) (Suemitsu)