

博士論文（要約）

Study on Si hybrid MOS optical modulators

by using wafer bonding

（基板貼り合わせを用いた Si ハイブリッド

MOS 型光変調器に関する研究）

平成 28 年 12 月 1 日提出

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Abstract

Silicon (Si) photonics is a promising solution for high-speed, high-density and low-power optical communication. Especially, a Si optical modulator is one of important components for changing electrical signals to optical signals. However, due to small plasma dispersion effect of Si, its modulation efficiency is one of limitations for the further improvement of Si photonics platform. Therefore, it is necessary to improve its device performance for a Si photonics platform. Among the structures of Si optical modulators, an MOS optical modulator based on poly-Si/SiO₂/Si MOS structure is the most promising solution for achieving high performance in terms of modulation efficiency and modulation bandwidth. However, although the modulation efficiency of MOS optical modulator is easily improved by the thinning of the SiO₂ thickness because its accumulated carrier at MOS capacitor is increased, modulation bandwidth is also degraded because its large capacitance of MOS capacitor. Therefore, it is difficult to achieve further improvement of MOS optical modulator due to this unavoidable trade-off relationship. To break through this trade-off relationship, introducing new materials, which have larger free-carrier effect with light than Si, is promising. Among many materials, silicon-germanium (SiGe) for replacing *p*-type Si and indium gallium arsenide phosphide (InGaAsP) for replacing *n*-Si are the most promising solutions for enhancing the free-carrier effect of each carrier owing to their small effective mass. We have also analyzed these carrier effect of these materials to estimate the enhancement of the performance using new materials.

To introduce these new materials into Si photonics platform and enhance the performance of MOS optical modulators, we have proposed a hybrid MOS optical

modulator fabricated by direct wafer bonding. This structure can easily achieve hybrid MOS structure with different materials; thus, we can easily control the effect of carrier by changing materials. To achieve this structure, the void-free direct wafer bonding technique have been established. Then, we have also established the fabrication technique of a hybrid MOS optical modulator to demonstrate an ultra-high-performance optical modulator. The electrical properties of MOS interface have also been estimated for high quality MOS structure.

Using this technique, we focus on InGaAsP/Si hybrid MOS optical modulator indium gallium arsenide phosphide (InGaAsP) lattice-matched to indium phosphide (InP) which has large electron-induced free-carrier effect. In this study, we discuss the electron-induced free-carrier effect of InGaAsP which has the larger effect than Si and InP. By using this electron-induced free-carrier effect, the modulation efficiency of an InGaAsP/Si hybrid MOS optical modulator is estimated. This structure also allow us to achieve low optical loss and low resistance by replacing poly-Si to crystalline InGaAsP which has good crystal quality and high electron mobility. Therefore, an InGaAsP/Si hybrid MOS optical modulator can realize high modulation efficiency with low optical loss and high modulation bandwidth. Owing to InGaAsP, record-high modulation efficiency is achieved, which is approximately five times higher than conventional Si devices.

SiGe is also promising material for enhancing the effect of hole. We have numerically analysis of its effect on modulation bandwidth and modulation efficiency owing to its high mobility and small effective mass of hole. We can expect approximately 1.3 times higher modulation efficiency and modulation bandwidth owing to the small resistance and large hole-induced refractive index change.

We proposed and demonstrated high-efficiency hybrid MOS optical modulator using wafer bonding. Especially, in case of InGaAsP/Si hybrid MOS optical modulator, we achieved the ultra-low phase modulation efficiency, which was one of the best values among semiconductor-based optical modulators. The presented modulator needs less charges for π phase shift as compared with Si-based optical modulators, enabling low optical insertion loss simultaneously. Thus, the hybrid MOS phase shifter is, in particular, useful for optical modulators with advanced modulation formats and optical switches. Since various semiconductors including SiGe, Ge, and other III-V semiconductors can be integrated by the presented scheme, the hybrid MOS structures will provide many applications for near and mid infrared wavelengths.

Acknowledgments

I would like to express my sincere appreciation to my academic advisor, Associate Professor Mitsuru Takenaka for his guidance, encouragement and continuous advices through the course of this work. I always have been impressed with his insights into researches what I have carried out over my master course; thus I can complete this thesis. I also would like to express my gratitude to Professor Shinichi Takagi for his supports, and suggestions. His broad knowledge of MOS device always helps me understand many issues in my researches.

I must thank all the members of Takagi-Takenaka group for their encouragement and advice. And, I would like to express my special thanks to Ms. Noriko Uchima for her helps of official works.

I would like to thank to the member of Sumitomo Chemical Co. Ltd., Dr. Masafumi Yokoyama for his supports. They have provided wafers what I used in my researches. I also wish to record special thanks to the Japan Society for the Promotion of Science (JSPS) for their financial supports.

Finally, I want to sincerely thank to my mother, JungSook Jang and my brother, JaeMin Han for their constant supports. I also wish to express my gratitude and pray that his soul rest in peace to my late father, YoungHwan Han.

Thanks to their grate guidance and helps, I can complete this thesis. And, I also have many chances to present papers in many conferences and journals. I would like to take this opportunity to express my deep gratitude again.

1st Dec. 2016

Jae-Hoon Han

Through this thesis, a Si hybrid MOS optical modulator with new materials such as InGaAsP and SiGe fabricated by direct wafer bonding have been investigated. We have been discussed the numerical analysis for these materials and fabrication issues for realizing the hybrid MOS optical modulator.

Si photonics is a promising solution for future high-speed interconnect¹. However, the performance of active devices on Si photonics is not enough due to the material limitation of Si. Especially, in this thesis, we have focused on a high-performance Si hybrid MOS optical modulator for Si photonics platform². Conventional Si MOS optical modulator can achieve high modulation efficiency compared to other structures such as pn junction owing to its large accumulation carriers³⁻⁹. Furthermore, we can easily enhance its modulation efficiency by EOT scaling. However, EOT scaling causes the degradation on the modulation bandwidth of MOS optical modulator due to its enlarged capacitance; thus, there is a trade-off relationship between modulation efficiency and bandwidth. To overcome this trade-off relationship, introducing new material is a promising solution. According to the principle of free-carrier effect, new materials which have small effective mass are promising to enhance the free-carrier effects in the semiconductor; thus, SiGe for hole¹⁰ and InGaAsP for electron^{11,12} are promising candidates to achieve ultra-high modulation efficiency of Si optical modulator. To introduce these materials, we have investigated direct wafer bonding with high-k dielectrics such as Al₂O₃ and HfO₂. We have also discussed its MOS interface because MOS interface is the most important issue for high-performance MOS devices. We have also investigated the effect of these new materials on the device performance by numerical analysis. Finally, we have demonstrated these Si hybrid MOS optical modulators.

In chapter 2, we have established a void-free direct wafer bonding technique using $\text{HfO}_2/\text{Al}_2\text{O}_3$. Pre-bonding annealing and long water purge time is essential for reducing voids on the bonded wafer using Al_2O_3 . However, only Al_2O_3 cannot eliminate voids completely after post-bonding annealing. To solve this problem, we have introduced HfO_2 . From TDS measurement, we observed water and carbon-oriented degas from high-k layer is successfully reduced owing to the low contamination level of HfO_2 .

In chapter 3, to improve high-k/SiGe MOS interface, we have investigated the effect of plasma post-nitridation on the interface trap density of $\text{Al}_2\text{O}_3/\text{SiGe}$ MOS interfaces with a high Ge composition and various surface orientation such as (110) and (100). We successfully confirmed its effects on the MOS interface of high-k/SiGe. We have also established the high-temperature conductance method for eliminating the impedance of Si/SiGe hetero-interface.

In chapter 4, we have investigated the effect of the strained p -SiGe to reduce the resistance of the slab for high-speed MOS optical modulators. SiGe can reduce the total resistance of the device owing to its small resistivity extracted by its higher mobility than Si. Furthermore, SiGe can also enhance the modulation efficiency thanks to its smaller effective mass than Si. Therefore, using $\text{Si}_{0.8}\text{Ge}_{0.2}$, we can achieve 1.3 times higher modulation bandwidth and 1.4 times higher modulation efficiency compared to conventional Si MOS optical modulator.

In chapter 5, we have investigated the MOS interface of wafer-bonded high-k/III-V MOS capacitor. We have confirmed the superior C-V characteristics of n - $\text{InGaAsP}/\text{Al}_2\text{O}_3/p^+-\text{Si}$ and n - $\text{InGaAsP}/\text{Al}_2\text{O}_3/\text{HfO}_2/p^+-\text{Si}$ MOS capacitors. We have also confirm low D_{it} around $10^{11} \text{ eV}^{-1}\text{cm}^{-2}$ of them, which is relatively low value compared to other high-k/III-V MOS interface.

In chapter 6, we have discussed numerical analysis of InGaAsP/Si hybrid MOS optical modulator. Owing to the large electron-induced refractive index change of n-type InGaAsP, InGaAsP/Si hybrid MOS optical modulator can achieve approximately 5-time-high modulation efficiency. Furthermore, thanks to high electron mobility of InGaAsP, free carrier absorption caused by electron is reduced compared to Si. Therefore, InGaAsP can realize low loss with high modulation efficiency. The resistivity of n-type InGaAsP is also smaller than Si because of its small mobility; thus, InGaAsP allows us to achieve broader modulation bandwidth compared to conventional Si MOS optical modulator.

In chapter 7, we successfully demonstrated a high-efficiency MZI optical modulator with an InGaAsP/Si hybrid MOS phase shifter using direct wafer bonding. We achieved a high phase modulation efficiency, which are, to the best of our knowledge, one of the best values reported for semiconductor-based optical modulators. The modulation efficiency is improved by approximately 5 times for C-band. The presented modulator needs fewer charges for π phase shift than Si-based optical modulators, enabling approximately 10-time-low optical insertion loss simultaneously.

Therefore, our Si hybrid MOS optical modulator is a promising solution for future high-performance Si photonics platform. It can realize high modulation efficiency, high modulation bandwidth, and lower optical loss, especially in case of InGaAsP/Si hybrid MOS optical modulator. Therefore, the InGaAsP/Si hybrid MOS phase shifter is also expected to be particularly useful for optical modulators with advanced modulation formats and optical switches. Since various semiconductors including SiGe, Ge, and other III-V semiconductors can be integrated using the presented scheme, the hybrid MOS structures are expected to provide many applications for near- and mid-infrared wavelengths.

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Lists of publication

1. Publication as the first author

A) Journals

- [1] J.-H. Han, M. Takenaka, and S. Takagi, "Analysis of interface trap density of plasma post-nitrided Al₂O₃/SiGe MOS interface with high Ge content using high-temperature conductance method", *J. Appl. Phys.*, vol. 120, 125707, 2016. DOI: 10.1063/1.4963877
- [2] J.-H. Han, M. Takenaka, and S. Takagi, "Study on void reduction in direct wafer bonding using Al₂O₃/HfO₂ bonding interface for high-performance Si high-k MOS optical modulators," *Jpn. J. Appl. Phys.*, Vol. 55, 04EC06, 2016. DOI: 10.7567/JJAP.55.04EC06

B) International conferences

- [1] (Oral presentation) J.-H. Han, M. Takenaka, and S. Takagi, "High-efficiency O-band Mach-Zehnder modulator based on InGaAsP/Si hybrid MOS capacitor," *2017 Optical fiber conference (OFC'17)*, W3E.2, Los Angeles, 22 March 2017.
- [2] (Oral presentation) J.-H. Han, M. Takenaka, and S. Takagi, "Extremely high modulation efficiency III-V/Si hybrid MOS optical modulator fabricated by direct wafer bonding," *International Electron Devices Meeting (IEDM'16)*, 25.5, San Francisco, 7 December 2016.
- [3] (Poster presentation) J.-H. Han, M. Takenaka, and S. Takagi, "Estimation of modulation efficiency enhancement using an InGaAsP/Si hybrid MOS optical modulator," *6th International Symposium on Photonics and Electronics Convergence (ISPEC2016)*, P-15, Tokyo, 29 November 2016.
- [4] (Poster presentation) J.-H. Han, M. Takenaka, and S. Takagi, "Feasibility study of III-V/Si hybrid MOS optical modulators consisting of n-InGaAsP/Al₂O₃/p-Si MOS capacitor formed by wafer bonding," *International Conference on Group IV Photonics (GFP2016)*, ThP16, Sanghai, China, 25 August 2016.
- [5] (Poster presentation) J.-H. Han, M. Takenaka, and S. Takagi, "Bandwidth enhancement of Si MOS optical modulators using strained SiGe slab," *5th International Symposium on Photonics and Electronics Convergence (ISPEC2015)*, P-41, Tokyo, 1 December 2015.
- [6] (Oral presentation) J. Han, M. Takenaka, and S. Takagi, "Improvement in

the modulation bandwidth of MOS optical modulators by using p-SiGe slab," *Asia Communications and Photonics Conference (ACP 2015)*, ASu5B.2, Hong Kong Convention and Exhibition Center, Hong Kong, 22 November 2015.

- [7] (Oral presentation) J. Han, M. Takenaka, and S. Takagi, "Suppression of void generation in direct wafer bonding for Si high-k MOS optical modulators using $\text{Al}_2\text{O}_3/\text{HfO}_2$ bonding interface," *International Conference on Solid State Devices and Materials (SSDM2015)*, A-3-4, Sapporo Convention Center, 29 September 2015.
- [8] (Oral presentation) J.-H. Han, M. Takenaka, and S. Takagi, "Comparison of $\text{Al}_2\text{O}_3/\text{Si}_{1-x}\text{Ge}_x$ MOS interfaces grown on p-Si (100) and p-Si (110) with plasma post-nitridation," *IEEE Semiconductor Interface Specialists conference (SISC2014)*, 13.4, San Diego, USA, 13 December 2014.

C) Domestic conferences

- [1] (Oral presentation, invited) 韓 在勲, 高木 信一, 竹中 充, 「貼り合わせ法を用いた高性能 InGaAsP/Si hybrid MOS 型光変調器」, 第 77 回応用物理学会秋季学術講演会, 16p-F204-7, パシフィコ横浜, 神奈川, 2017 年 3 月 16 日.
- [2] (Oral presentation) 韓 在勲, 竹中 充, 高木 信一, 「貼り合わせ InGaAsP/Si ハイブリッド MOS 型光変調器に関する検討」, 第 77 回応用物理学会秋季学術講演会, 14p-B4-2, 朱鷺メッセ, 新潟, 2016 年 9 月 14 日.
- [3] (Oral presentation) 韓 在勲, 竹中 充, 高木 信一, 「歪 SiGe を用いた MOS 型光変調器の変調帯域改善に関する検討」, 第 63 回応用物理学会春季学術講演会, 21p-S611-7, 東京工業大学大岡山キャンパス, 2016 年 3 月 21 日.
- [4] (Poster presentation) 韓 在勲, 竹中充, 高木信一, 「貼り合せ MOS 型光変調器実現に向けた $\text{Al}_2\text{O}_3/\text{HfO}_2$ 界面によるボイド低減手法の検討」, 第 76 回応用物理学会秋季学術講演会, 14p-PA4-5, 名古屋国際会議場, 2015 年 9 月 14 日.
- [5] (Oral presentation) 韓 在勲, 竹中 充, 高木 信一, 「プラズマ後窒化 (100)面及び(110)面 SiGe MOS 界面の比較」, 第 62 回応用物理学会春季学術講演会, 14a-A24-4, 東海大学湘南キャンパス, 2015 年 3 月 14 日.
- [6] (Oral presentation) 韓在勲, 竹中充, 高木信一, 「プラズマ後窒化 $\text{HfO}_2/\text{Al}_2\text{O}_3/\text{SiGe}_{0.32}$ MOS 界面の電極依存性」, 第 75 回応用物理学会

秋季学術講演会, 19p-A17-7, 北海道大学札幌キャンパス, 2014年9月19日.

2. Publication as non-first author

A) Journals

- [1] (Invited, published in online) M. Takenaka, Y. Kim, J. Han, J. Kang, Y. Ikku, Y. Cheng, J. Park, M. Yoshida, S. Takashima, and S. Takagi, "Heterogeneous CMOS photonics based on SiGe/Ge and III-V semiconductors integrated on Si Platform", *IEEE J. Sel. Top. Quantum Electron.*, 2017. DOI: 10.1109/JSTQE.2017.2660884
- [2] (Invited) M. Takenaka, Y. Kim, J. Han, J. Kang, and S. Takagi, "Challenges and opportunities of near and mid-infrared photonics based on SiGe and Ge," *ECS Trans.*, vol. 75, no. 8, pp. 447-459, 2016. DOI: 10.1149/07508.0447ecst
- [3] J.-K. Park, J. Han, M. Takenaka, and S. Takagi, "InGaAsP variable optical attenuator with lateral P-I-N junction formed by Ni-InGaAsP and Zn diffusion on III-V on insulator wafer," *MRS Advances*, Vol. ??, ??, 2016. DOI: 10.1557/adv.2016.339
- [4] (Invited) S. Takagi, C. Y. Chang, M. Yokoyama, K. Nishi, R. Chang, M. Ke, J. H. Han, and M. Takenaka, "MOS interface control technologies for advanced III-V/ Ge devices," *ECS Trans.*, vol. 69, no. 5, pp. 37-51, 2015. DOI: 10.1149/06905.0037ecst
- [5] Y. Kim, J. Han, M. Takenaka, and S. Takagi, "Low temperature Al₂O₃ surface passivation for carrier-injection SiGe optical modulator", *Optics Express*, vol. 22, no. 7, pp. 7458-7464, 2014. DOI: 10.1364/OE.22.007458
- [6] N. Yoshida, E. Waki, M. Arai, K. Yamasaki, J.-H. Han, M. Takenaka, and S. Takagi, "Extraction of interface state density at SiO₂/SiC interfaces based on impedance measurements with different temperatures", *Thin Solid Films*, vol. 557, no. 30, pp. 237-240, 2014.

B) International conferences

- [1] (Oral presentation) M. Takenaka, Y. Ozawa, J. Han, and S. Takagi, "Quantitative evaluation of energy distribution of interface trap density at MoS₂ MOS interfaces by the Terman method," *International Electron Devices Meeting (IEDM '16)*, 5.8, San Francisco, 5 December 2016.
- [2] (Oral presentation, invited) M. Takenaka, Y. Kim, J. Han, J. Kang, and S. Takagi, "Challenges and opportunities of near and mid-infrared photonics based on SiGe and Ge," *230th ECS Meeting*, Symposium G05, 1968, Hawaii,

USA, 4 October 2016.

- [3] (Oral presentation, invited) M. Takenaka, Y. Kim, J. Han, J. Kang, and S. Takagi, "CMOS photonics based on SiGe and Ge for near and mid-infrared photonic integrated circuits," *International Conference on Solid State Devices and Materials (SSDM2016)*, C-3-1, Tukuba, 28 September 2016.
- [4] (Oral presentation) N. Sekine, J. Han, M. Takenaka, and S. Takagi, "Numerical analysis of InGaAsP carrier-depletion optical modulator on III-V CMOS photonics platform," *International Conference on Solid State Devices and Materials (SSDM2016)*, PS-7-11, Tukuba, 28 September 2016.
- [5] (Oral presentation) J. Fujikata, M. Noguchi, J. Han, S. Takahashi, M. Takenaka, and T. Nakamura, "Record-high Modulation-efficiency Depletion-type Si-based optical modulator with in-situ B doped strained SiGe layer on Si waveguide for 1.3 μm wavelength," *European Conference on Optical Communication (ECOC 2016)*, Düsseldorf, Tu3.A.4, 20 September 2016.
- [6] (Oral presentation, invited) M. Takenaka, Y. Kim, J. Han, J. Kang, Y. Ikku, Y. Cheng, J. Park, and S. Takagi, "CMOS photonics technologies based on heterogeneous integration of SiGe/Ge and III-V on Si," *Proc. SPIE 9891 (SPIE Photonics Europe)*, Silicon Photonics and Photonic Integrated Circuits V, 98911H, Brussels, 4-7 April 2016. DOI: 10.1117/12.2227457
- [7] (Oral presentation, invited) M. Takenaka, Y. Kim, J. Han, J. Kang, Y. Ikku, Y. Cheng, J.-K. Park, S.-H Kim, and S. Takagi, "CMOS photonics technologies based on heterogeneous integration of SiGe/Ge and III-V on Si," *International Electron Devices Meeting (IEDM'15)*, 31.5, Washington D.C., 9 December 2015. DOI: 10.1109/IEDM.2015.7409809
- [8] (Oral presentation) J. Fujikata, M. Noguchi, Y. Kim, J. Han, S. Takahashi, T. Nakamura, and M. Takenaka, "High Speed and Highly Efficient Si Optical Modulator with Strained SiGe Layer," *5th International Symposium on Photonics and Electronics Convergence (ISPEC2015)*, P-4, Tokyo, 1 December 2015.
- [9] (Oral presentation, invited) S. Takagi, W.-K. Kim, X. Yu, J. Han, R. Zhang, M. Takenaka, "Ge/SiGe CMOS device technology for future logic LSIs," *E-MRS Spring Meeting*, Symposium K.1, Lille, France, 14 May 2015 (*invited*).
- [10] (Oral presentation, invited) S. Takagi, R. Zhang, C.-Y. Chang, J.-H. Han, M. Yokoyama, K. Nishi, and M. Takenaka, "Gate stack technologies for high mobility channel MOSFETs," *MRS Spring Meeting*, Symposium AA, 10.02,

San Francisco, USA, 9 April 2015.

C) Domestic conferences

- [1] (Oral presentation) 藤方 潤一, 高橋 重樹, 野口 将高, ハン ジェフン, 堀川 剛, 屋敷 健一郎, 栗原 充, 萩原 靖彦, 竹中 充, 中村 隆宏, 蔵田 和彦, 「産総研 SCR を利用した Si フォトニクスデバイスの開発および光 I/O コアへの適用」, 電子情報通信学会第 25 回シリコンフォトニクス研究会, 石垣市商工会館, 2016 年 12 月 8-9 日.
- [2] (Oral presentation) 藤方 潤一, 野口 将高, 韓 在勲, 高橋 重樹, 竹中 充, 中村 隆宏, 「in-situ B ドーピングした歪 SiGe 層を用いた Si 光変調器の検討(II)」, 第 77 回応用物理学会秋季学術講演会, 15p-B8-5, 朱鷺メッセ, 新潟, 2016 年 9 月 15 日.
- [3] (Oral presentation) 武内 和治, 韓 在勲, 竹中 充, 高木 信一, 「楕円 PN 接合型 Si 光変調器におけるイオン注入による横方向不純物分布の影響」, 第 77 回応用物理学会秋季学術講演会, 14a-B4-2, 朱鷺メッセ, 新潟, 2016 年 9 月 14 日.
- [4] (Oral presentation) 朴 珍權, 韓 在勲, 竹中 充, 高木 信一, 「III-V CMOS フォトニクス・プラットフォーム上キャリア注入型 InGaAsP 可変光減衰器」, 第 77 回応用物理学会秋季学術講演会, 14p-B4-3, 朱鷺メッセ, 新潟, 2016 年 9 月 14 日.
- [5] (Oral presentation) 関根 尚希, 韓 在勲, 竹中 充, 高木 信一, 「III-V CMOS フォトニクス・プラットフォーム上 空乏型 InGaAsP 光変調器の検討」, 第 63 回応用物理学会春季学術講演会, 21p-S611-4, 東京工業大学大岡山キャンパス, 2016 年 3 月 21 日.
- [6] (Oral presentation) 野口将高, 藤方潤一, 高橋重樹, 韓 在勲, 中村隆宏, 竹中 充, 「歪 SiGe を用いた Si 光変調器の作製プロセス検討」, 電子情報通信学会総合大会, C3-30, 九州大学伊都キャンパス, 2016 年 3 月 16 日.
- [7] (Oral presentation) 竹中 充, 金 栄現, 韓 在勲, 亢 健, 一宮佑希, 程 勇鵬, 朴 珍權, 金 相賢, 高木信一, 「Si 上異種半導体集積による CMOS フォトニクス」, 電子情報通信学会 SDM 研究会・応用物理学会シリコンテクノロジー分科会共催研究集会, 機会振興会館, 2016 年 1 月 28 日 (招待講演) .
- [8] (Oral presentation) 野口 将高, 韓 在勲, 藤方 潤一, 中村 隆宏, 竹中 充, 「Si 光変調器に向けた歪 SiGe 成長に関する検討」, 第 62 回応用物理学会春季学術講演会, 12a-A16-10, 東海大学湘南キャンパス,

2015年3月12日.

3. Awards

- A) 第41回応用物理学会講演奨励賞
- B) 15th IEEE EDS Japan Chapter Student Award

4. Patents

- A) Method of producing semiconductor wafer, semiconductor wafer, method of producing semiconductor device and semiconductor device, US9117658 (2015).
- B) (出願) MO S型光変調器及びその製造方法、特願2016-160229