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研究課題名（和文）Development of quasi-2D Si devices with large magnetoresistance

研究課題名（英文）Development of quasi-2D Si devices with large magnetoresistance

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研究成果の概要（和文）：目標は、電子スピンを利用して情報を処理・保存するシリコンベースの磁気抵抗効果デバイスを開発することである。このようなデバイスを動作させるための主要な前提条件は、シリコンの2端子（2T）磁気抵抗（MR）を大きくすることである。そこでわれわれは、2つの相補的なアプローチを検討した。(1)薄いシリコン・チャネルと磁気トンネル・コンタクトを用いて2Tデバイスを作製し、(2)スピン注入効率を向上させるために、新しいトンネル障壁であるBaOの成長を検討した。薄いSiチャネルを用いることで有望な結果が得られたが、Si上に高品質のBaOトンネル障壁を成長させることは非常に困難であることが判明した。

研究成果の学術的意義や社会的意義
We investigated two novel approaches to increase the MR and determined optimum contact resistance for large MR in Si-based spin transport devices. The results are essential to design silicon devices with large MR and open exciting applications in areas ranging from electronics to quantum computing.

研究成果の概要（英文）：The goal is to develop silicon-based magnetoresistive devices that use the electron spin to process and store information. A major prerequisite for the operation of such devices is to obtain a sizeable two-terminal (2T) magnetoresistance (MR) in silicon. Thus, we investigated two complementary approaches: (1) we fabricated 2T devices with thin silicon channels and magnetic tunnel contacts, and (2) we investigated the growth of a novel tunnel barrier, BaO, to improve the spin injection efficiency. Whereas promising results were achieved by using thin Si channels, the growth of high-quality BaO tunnel barrier on Si proved to be very difficult.

研究分野：ナノ構造物理関連

キーワード：silicon spintronics　magnetic tunnel contact　magnetoresistance　spin transport　tunnel barrier

１．研究開始当初の背景

In conventional electronics, the electron charge is used for information processing in semiconductors devices, whereas the electron spin is used for long-term data storage in magnetic materials. In recent decades, the continuous downscaling of transistors has led to the increased power dissipation due to leakage currents. Therefore information-processing systems that use the spin as a state variable offer appealing opportunities to develop alternative energy-efficient electronics.

Prerequisite for the operation of a device that combines the functions of a traditional transistor with that of a two-terminal magnetoresistive device is two-fold: first, efficient injection, transport, manipulation and detection of spin-polarized carriers in a lateral semiconductor channel must be achieved. Second, a sizeable two-terminal magnetoresistance (2T-MR) must be obtained. Over the last decade, several groups have reported the electrical injection, transport and detection of spins in Si [1-5], fulfilling the first prerequisite. However, the 2T-MR ratios in Si have been so far very limited (0.1-1% [6,7]). Hence, finding new ways to significantly enhance the 2T-MR in Si-based devices is crucial to advance the technological impact of Si-based spin-MOSFET.

２．研究の目的

The aim of this project is to demonstrate that a large 2T-MR can be obtained in a Si device with ferromagnetic (FM) source and drain contacts by using an ultrathin Si channel with highly-spin polarized magnetic tunnel contacts. On the one hand, the reduction of the Si channel thickness to quasi-two-dimensional (2D) will enhance the magnetic signal for a given contact resistance. On the other hand, the development of novel epitaxial ferromagnet/oxide tunnel contacts on Si is expected to improve the spin injection efficiency. By combining these two approaches, a sizeable magnetoresistance is anticipated.

３．研究の方法

Theoretical calculations have shown that a large 2T-MR can only be achieved if the contact resistance-area product (RA) of the FM tunnel contact falls within a narrow range that depends on parameters such as the silicon channel resistivity [8]. Most importantly, it is predicted that by reducing the channel thickness, a large MR can be achieved at a RA for which a high spin injection efficiency is still observed. Therefore, one way to enhance the 2T-MR in Si is to reduce the channel thickness to quasi-two-dimensional (2D), while keeping the resistivity constant.

Another limitation to the 2T-MR in Si is the poor crystalline quality of ultrathin MgO tunnel barrier due to the large lattice mismatch between Si and MgO (~ 22%).

Because the optimum MR value is proportional to the spin injection efficiency (*P*), it is necessary to increase *P* for contacts having lower RA (i.e. thinner oxide tunnel barrier). To solve this issue, we propose to fabricate fully epitaxial FM/oxide tunnel contacts on Si using a novel oxide tunnel barrier BaO. This oxide is better lattice-matched to Si compared to MgO and therefore, it can potentially act as a better spin-filter on Si.

４．研究成果

As a first step, we examined the scaling of the 2T-MR as a function of the contact resistance in devices with a Si channel and Fe/MgO tunnel contacts. The experiments were performed on devices with a 70 nm thick, heavily doped n-type Si(001) channel having two crystalline Fe/MgO/ Si tunnel contacts. The 2T-MR is obtained by applying a current between the two ferromagnetic contacts and measuring the two-terminal voltage between the same contacts as a function of the external magnetic field applied in-plane and along the long axis of the FM contacts. The contact RA-product spans range well over 2 orders of magnitude and includes values that are only a factor of 1.7 away from the optimum value. For the calculations of the 2T-MR, we use the *P* values extracted from nonlocal spin-transport measurements in the same devices for each MgO thickness. This enables a quantitative comparison between experiment and theory. It is shown that the scaling and the optimum of the 2T-MR are profoundly different from what the theory predicts [9]. This behavior can be explained by the fact that the *P* of the magnetic tunnel contacts is not constant when the barrier thickness is varied. It is, thus, crucial to take this into account in the design and optimization of practical 2T-MR devices.

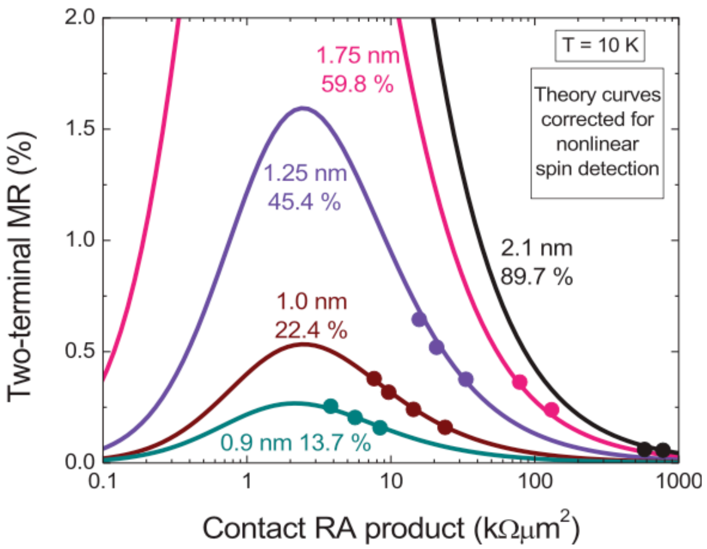

Fig. 1: The 2T-MR at 10 K as a function of the RA-product of the Fe/MgO magnetic tunnel contacts. Solid symbols are the experimental data for devices and solid lines represent the calculated 2T-MR. Labels denote the MgO thickness and the tunnel spin polarization *P* in %. Note that all the values are shown after correction for the nonlinear spin detection, as explained in Ref.9.

Next, we fabricated spin-transport devices with Fe/MgO tunnel contact and a lateral Si channel having different thicknesses, ranging from 70 nm to 25 nm. The doping concentration of the Si channel remains constant, regardless of the thickness. As in the previous experiments, we used molecular beam epitaxy to epitaxially grow Fe/MgO. In all the fabricated devices, the Fe/MgO tunnel barrier exhibits similar high-crystalline quality, as indicated by the streaky reflection high-energy electron diffraction (RHEED) patterns. In addition, the exact same MgO thickness was deposited on all the devices, to ensure that the P is in the same order of magnitude. Because we encountered some technical difficulties during the device fabrication (critical step of etching the magnetic tunnel contact), our study has been significantly delayed. However, we are confident that the measurements of 2T-MR as a function of the channel thickness will give us some useful data to further improve our device design and, ultimately enhance the 2T-MR in Si.

Finally, we investigated the epitaxial growth of BaO on Si as a novel tunnel barrier. Different growth conditions such as the substrate surface reconstruction of the Si, the substrate temperature and the post-annealing temperature, were tested and compared, using in-situ RHEED technique, atomic force microscopy (AFM) and by probing the 2T resistance. Depending on the substrate temperature, the films turned out to be either BaO or metallic Ba due to the loss of oxygen at low growth temperatures. We achieved epitaxial BaO tunnel barrier on Si when the following growth conditions were used: (2x1) Si surface reconstruction, deposition of BaO at 625C without post-annealing. However, AFM measurements show a large roughness due to the presence of large grains of the deposited layer. This prevented us from fabricating spin-transport devices. More fine tuning of the growth conditions will be carried out to improve the crystalline quality as well as the roughness of the BaO barrier.

References:

[1] van ' t Erve *et al.*, Appl. Phys. Lett. **91**, 212109 (2007).
[2] T. Suzuki *et al.*, Appl. Phys. Express **4**, 023003 (2011).
[3] M. Ishikawa, *et al.,* Phys. Rev. B **95**, 115302 (2017).
[4] A. Spiesser, *et al.*, Phys. Rev. Appl. **8,** 064023 (2017).
[5] A. Spiesser, *et al.*, Phys. Rev. B **99**, 224427 (2019).
[6] T. Sasaki, et al., Appl. Phys. Lett. **104**, 052404 (2014).
[7] H. Koike, *et al.,* Appl. Phys. Express **13**, (2020).
[8] A. Fert and H. Jaffrès, Phys. Rev. B **64**, 1 (2001).
[9] A. Spiesser, et al. Appl. Phys. Lett. **122** 062407 (2023).

5．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

1．著者名 A. Spiesser, R. Jansen, H. Saito, and S. Yuasa	4．巻 122
2．論文標題 Optimum contact resistance for two-terminal magnetoresistance in a lateral spin valve	5．発行年 2023年
3．雑誌名 Applied Physics Letters	6．最初と最後の頁 1-6
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0137482	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Jansen R.、Spiesser A.、Fujita Y.、Saito H.、Yamada S.、Hamaya K.、Yuasa S.	4．巻 104
2．論文標題 Superimposed contributions to two-terminal and nonlocal spin signals in lateral spin-transport devices	5．発行年 2021年
3．雑誌名 Physical Review B	6．最初と最後の頁 144419
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.104.144419	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

1．発表者名 R. Jansen
2．発表標題 Two-Terminal Magnetoresistance in Lateral Spin-Valve Devices: Scaling with Contact Resistance
3．学会等名 Intermag 2023 Sendai(国際学会)（国際学会）
4．発表年 2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究協力者	ジャンセン　ロン (Jansen Ron)		

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関