様　式　C－19、F－19－1、Z－19　（共通）

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）ダイヤモンド反転型MOSFETにおけるチャネル移動度の制約因子の解明

研究課題名（英文）Limiting factor elucidation of channel mobility in inversion-type p-channel diamond MOSFETs

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：Al2O3酸化膜堆積前にH終端からOH終端に置換する表面処理を施したダイヤモンドMOSキャパシタを作製し、電気的特性評価を行った。その結果、MOSキャパシタにおいてはDitがMOSFETよりも低いことが明らかとなり、界面準位の特徴も理解が深まってきた。Ditは測定したエネルギー深さ領域において、2016年度に解析したMOSFETのDitよりも4分の1から一桁低い値であった。今後は、Al2O3酸化膜堆積前後の処理の効果についてMOSキャパシタによる詳細な解析で評価を行い、界面準位密度の起源を明らかにするとともに、Ditの低減、そして、電界効果移動度の増加を達成する。

研究成果の学術的意義や社会的意義
This study is meaningful for deep understanding of the interface states and is beneficial for developing more effective passivation techniques to improve the interface quality and device performance of diamond power MOSFETs, which is significant for the practical power application.

研究成果の概要（英文）：Aiming at the low channel mobility of world’s first inversion-type p-channel diamond MOSFETs, we focused on the main limiting factor of the high interface state density at Al2O3/diamond interface. We proposed a novel technique to form OH-termination by using the hydrogenated diamond surface followed by wet annealing. The interface quality is significantly improved. Also, the trap properties at Al2O3-diamond interface were examined by conductance method. Besides, we applied the OH-termination formation technique and successfully fabricated the inversion-type p-channel heteroepitaxial diamond MOSFETs and made the electrical characterization.

研究分野：semiconductor physics

キーワード：diamond　MOS　Interface

１．研究開始当初の背景(Background at the beginning of the Research)

Diamond has attracted much attention in power electronics due to its superior physical properties. Numerous studies have been devoted to the development of diamond power metal–oxide–semiconductor field-effect transistors (MOSFETs). In 2016, our group demonstrated the first inversion-type p-channel diamond MOSFET with normally off operation with Al_2O_3 film deposited on O-terminated diamond (111) surface followed by wet annealing. However, the inversion-type p-channel diamond MOSFET suffers from low field-effect mobility, which is mainly attributed to the existence of high interface state density (D_{it}) on the order of 10^{13} $cm^{-2}eV^{-1}$ near the valence band edge (E_v) of diamond.

２．研究の目的(Purpose of the Research)

To improve the channel mobility of inversion-type p-channel diamond MOSFETs, the D_{it} reduction and comprehensive understanding of trap properties are indispensable for improving the interface quality of Al_2O_3/diamond. Besides, the development of the heteroepitaxial diamond MOSFET is also significant because substrate size and cost of homoepitaxial diamond limit the commercialization. Therefore, in this study, we focused on the issues of the D_{it} reduction, Al_2O_3/diamond interface characterization, and the trail of heteroepitaxial diamond MOSFET.

３．研究の方法(Research Methods)

We employed a novel OH-termination formation technique that the IIb (111) diamond surface was treated by hydrogen-plasma exposure and subsequent wet vapor annealing and fabricated p-type diamond MOS capacitors where Al_2O_3 was used as the oxide formed by atomic layer deposition (ALD). The frequency-dependent C–V characteristics were examined at various temperatures. Furthermore, we applied the high temperature conductance method with considering the surface potential fluctuation to provide insights into the properties of interface states at Al_2O_3/diamond interface. In addition, by applying this surface termination technique, we fabricated the inversion-channel heteroepitaxially-grown freestanding diamond MOSFET where the diamond heteroepitaxy was realized on Ir/intermediate layer/Si (111) substrate.

４．研究成果(Research results)

The capacitance–voltage (C–V) curves from 1 Hz to 10 MHz at 400 K were demonstrated in Fig. 1. A hump in a C–V curve at 1 Hz was observed, and the magnitude of the hump decreased with increasing frequency, which indicates the existence of interface states at deep energy levels. Figure 2 shows the extracted D_{it} as a function of energy position from E_v of diamond extracted by the high-low method and conductance method. The extracted energy distribution of D_{it} by conductance method is consistent with that by high-low method, and we can deduce that the surface potential fluctuation is significant in the conductance method. By analyzing the energy distribution of surface potential fluctuation, we found that the Al_2O_3/diamond interface traps are donor-like, as shown in Fig. 3.

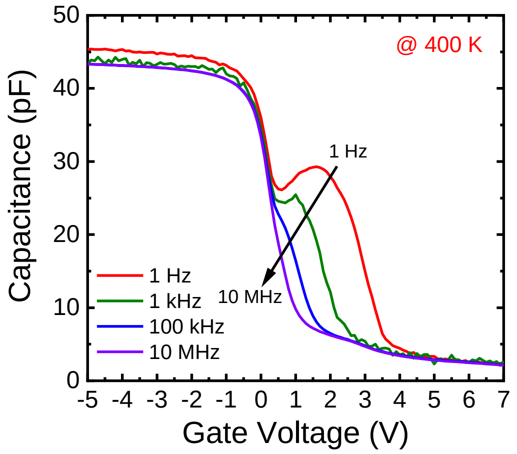

Fig. 1. Frequency-dependent *C*–*V* curves from 1 Hz to 10 MHz at 400 K.

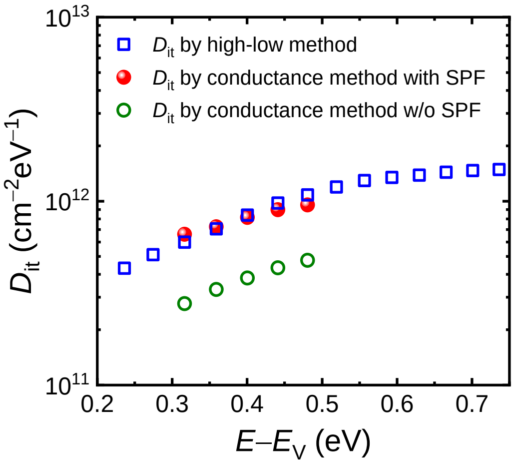

Fig. 2. Comparison of energy dependence of interface state density by high-low method, conductance methods with and without considering surface potential fluctuation.

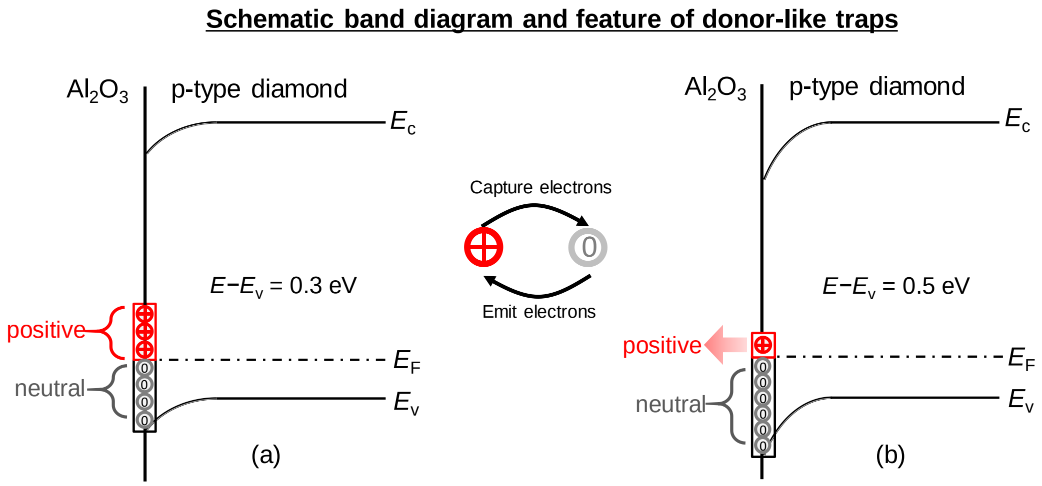

Fig. 3. Interpretation for the feature of donor-like traps using the band diagram, where (a) represents the Fermi level (E_F) approaching to the valence band edge (E_v) and (b) represents the E_F far from the E_v of diamond.

Figure 4 shows the top-view optical microscope image of the inversion-type p-channel heteroepitaxial diamond MOSFETs. The output (I_{ds}–V_{ds}) and transfer (I_{ds}–V_{gs}) characteristics were analyzed. The peak μ_{FE} of the heteroepitaxial diamond MOSFET reached 2.7 $cm^2V^{-1}s^{-1}$. This new finding would facilitate the practical application of the diamond power devices. In the next step, optimal heteroepitaxial growth conditions and lateral growth techniques are indispensable to improve the quality of diamond film and thus to enhance the device performance of the inversion-type p-channel heteroepitaxial diamond MOSFETs, which would facilitate the diamond device commercialization due to the low cost and large size.

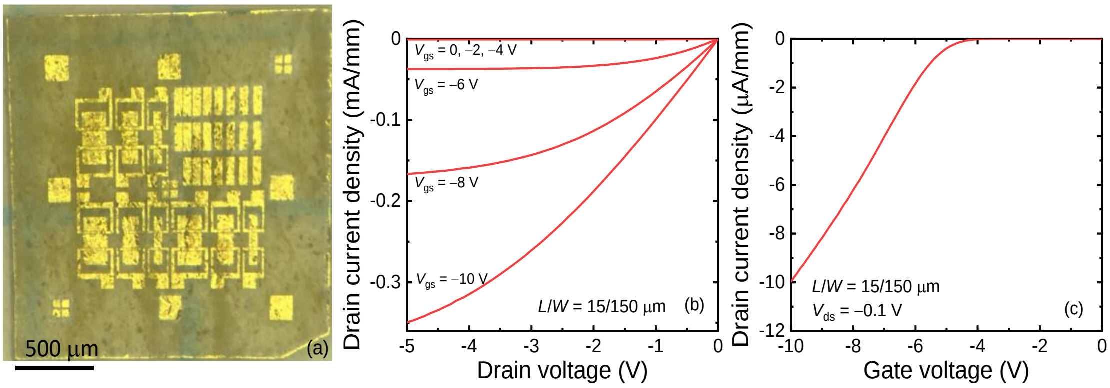

Fig. 4. (a) Top-view image of the inversion-type p-channel heteroepitaxial diamond MOSFETs by optical microscopy, (b) I_{ds}–V_{ds}, and (c) I_{ds}–V_{gs} characteristics for a typical MOSFET with L/W=15/150 μm.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　2件／うちオープンアクセス　3件）

１．著者名	４．巻
Xufang Zhang, Tsubasa Matsumoto, Ukyo Sakurai, Toshiharu Makino, Masahiko Ogura, Satoshi Yamasaki, Mitsuru Sometani, Dai Okamoto, Hiroshi Yano, Noriyuki Iwamuro, Takao Inokuma, and Norio Tokuda	168
２．論文標題	５．発行年
Energy distribution of Al2O3/diamond interface states characterized by high temperature capacitance-voltage method	2020年
３．雑誌名	６．最初と最後の頁
CARBON	659-664
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1016/j.carbon.2020.07.019	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	－

１．著者名	４．巻
Xufang Zhang, Tsubasa Matsumoto, Ukyo Sakurai, Toshiharu Makino, Masahiko Ogura, Mitsuru Sometani, Satoshi Yamasaki, Christoph E. Nebel, Takao Inokuma, and Norio Tokuda	117
２．論文標題	５．発行年
Insight into Al2O3/diamond interface states with high-temperature conductance method	2020年
３．雑誌名	６．最初と最後の頁
Applied Physics Letters	92104
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1063/5.0021785	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	該当する

１．著者名	４．巻
Xufang Zhang, Tsubasa Matsumoto, Yuta Nakano, Hitoshi Noguchi, Hiromitsu Kato, Toshiharu Makino, Daisuke Takeuchi, Masahiko Ogura, Satoshi Yamasaki, Christoph E. Nebel, Takao Inokuma, and Norio Tokuda	175
２．論文標題	５．発行年
Inversion channel MOSFET on heteroepitaxially grown free-standing diamond	2021年
３．雑誌名	６．最初と最後の頁
CARBON	615-619
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1016/j.carbon.2020.11.072	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	該当する

〔学会発表〕　計3件（うち招待講演　0件／うち国際学会　3件）

１．発表者名
Xufang Zhang, Tsubasa Matsumoto, Ukyo Sakurai, Toshiharu Makino, Masahiko Ogura, Satoshi Yamasaki, Mitsuru Sometani, Dai Okamoto, Hiroshi Yano, Noriyuki Iwamuro, Takao Inokuma, and Norio Tokuda
２．発表標題
Deep Interface Trap Analysis for Al2O3/Diamond MOS Structure by High-temperature Conductance Method
３．学会等名
NDNC（国際学会）
４．発表年
2021年

１．発表者名 Xufang Zhang, Tsubasa Matsumoto, Toshiharu Makino, Masahiko Ogura, Mitsuru Sometani, Dai Okamoto, Noriyuki Iwamuro, Satoshi Yamasaki, Christoph E. Nebel, Takao Inokuma, and Norio Tokuda
２．発表標題 High-temperature conductance analysis for Al203/diamond interface states
３．学会等名 IWDTF（国際学会）
４．発表年 2021年

１．発表者名 Xufang Zhang
２．発表標題 Deep Interface Trap Analysis for Al203/Diamond MOS Structure by High-temperature Conductance Method
３．学会等名 NDNC（国際学会）
４．発表年 2020年～2021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

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