世界初ダイヤモンド半導体パワー回路を開発

―高速スイッチング、長時間連続動作を実証－

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- 究極のパワー半導体物性をもつダイヤモンド半導体
- ダイヤモンド半導体デバイスのパワー回路を開発
- ダイヤモンド半導体パワー回路で１０ナノ秒を切る高速スイッチング動作
- ダイヤモンド半導体パワー回路で１９０時間の連続動作で特性劣化なし
- Beyond５G携帯基地局および電気自動車電力制御用デバイスに最適

N. C. Saha他, “Fast Switching NO_2-doped p-Channel Diamond MOSFETs”,
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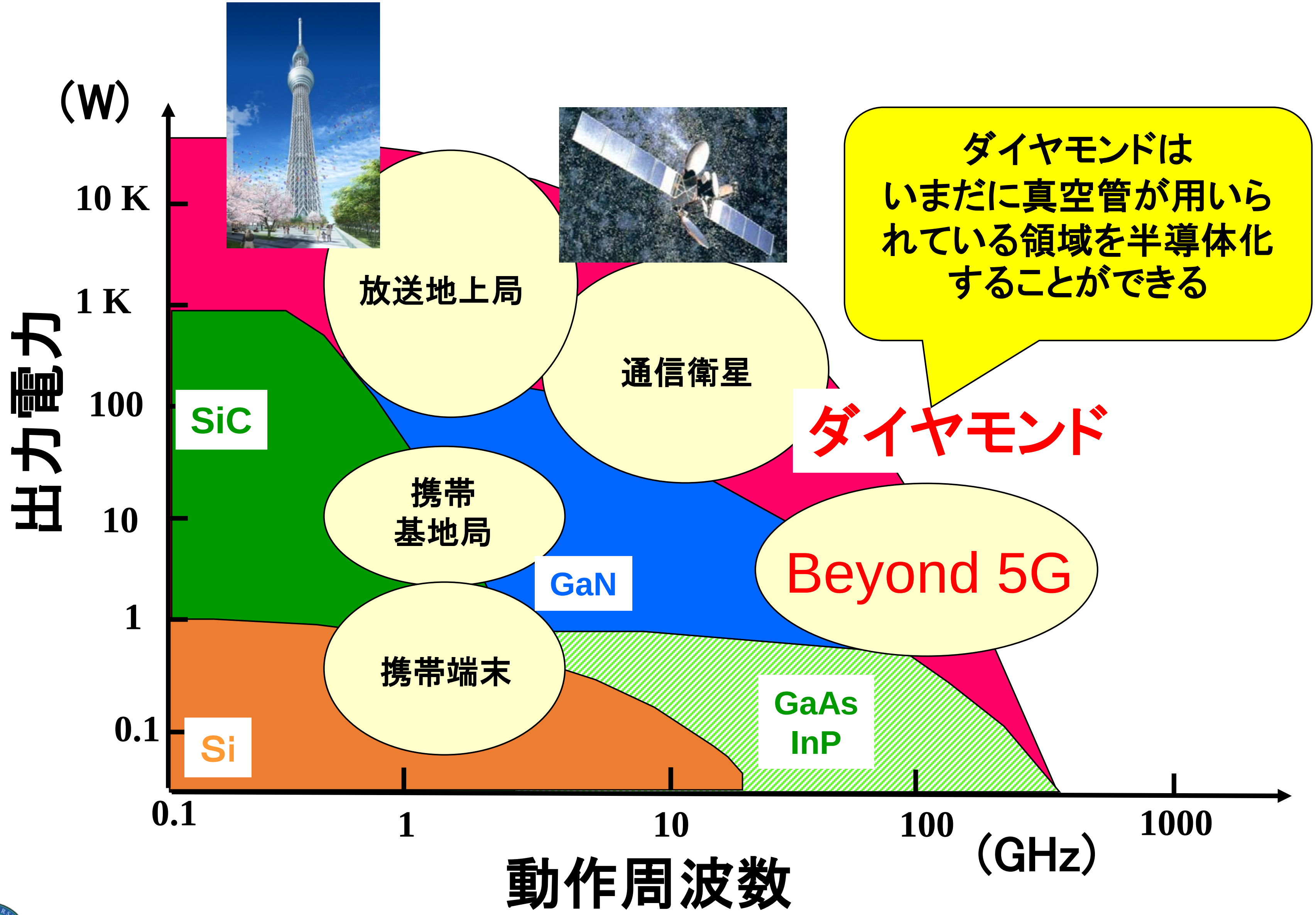
図１． 宇宙やBeyond5Gに向けた半導体の高周波化・高出力化の必要



ダイヤモンドは
いまだに真空管が用いら
れている領域を半導体化
することができる

（出所：嘉数、NTT Technical Journal, Vol. 8. No. 8（2010））

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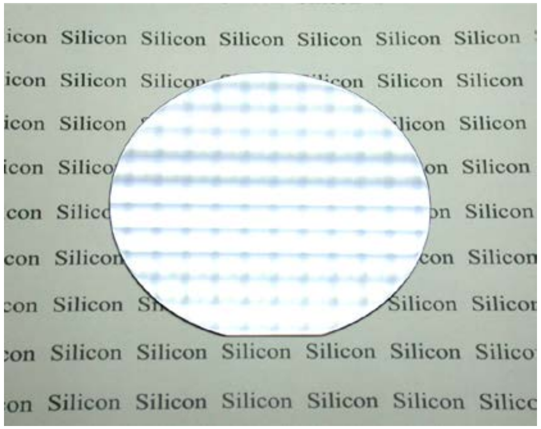
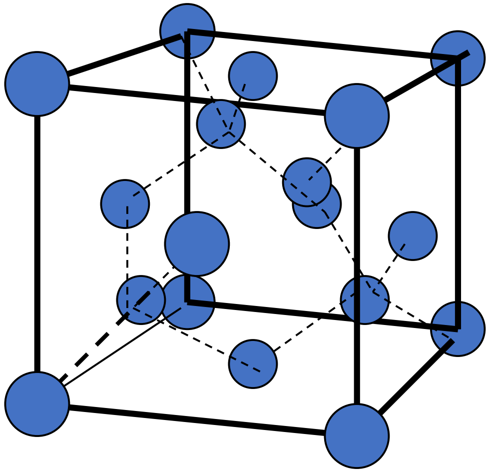
図２．ダイヤモンドの優れた物性から期待されるデバイス性能

ダイヤモンド

シリコン

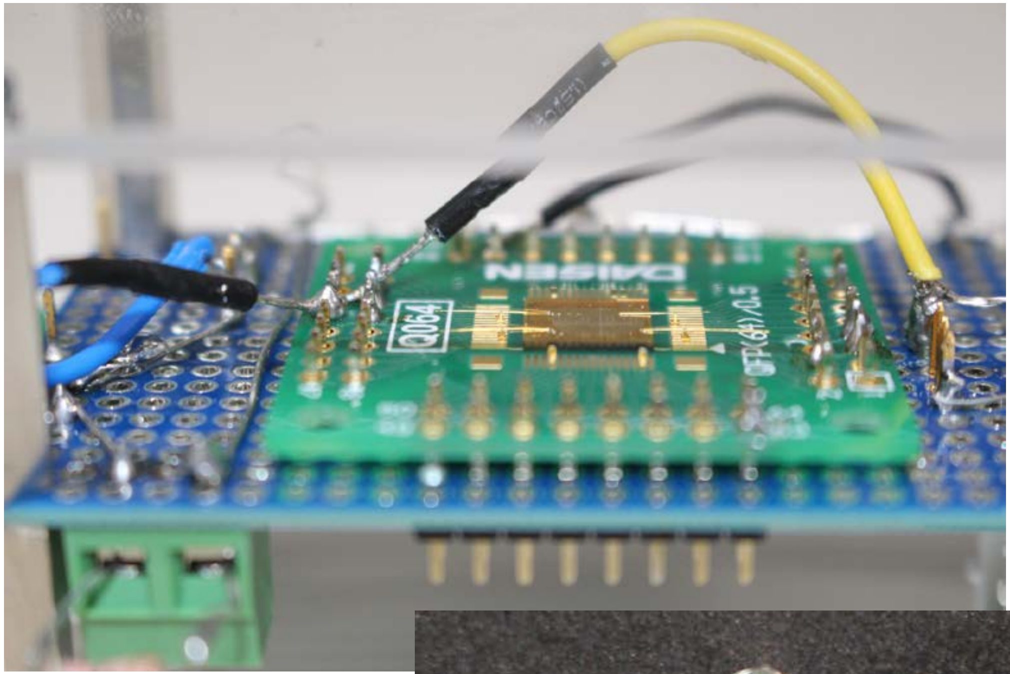


半導体の結晶構造



	シリコン	SiC	GaN	ダイヤモンド	ダイヤモンド半導体の特性
バンドギャップ	1	2.9	3.0	4.9	5倍の高温で動作
絶縁破壊電界強度	1	9.3	16.6	33	33倍の高電圧で動作
熱伝導度	1	3.8	1.2	17	17倍放熱しやすい。温度上昇がない。
バリガ性能指数	1	580	3,800	49,000	5万倍大電力で高効率のデバイス特性
ジョンソン性能指数	1	420	1,100	1,225	1,200倍の６G向け高速パワーデバイス特性

図３.技術ポイント(1)　ダイヤモンド半導体デバイスのパワー回路を開発



佐賀大学では、世界最高出力電力(875MWcm^{-2})、出力電圧(3659V)を報告

他機関では、劣化は早く、長時間動作は困難とされていた

実用では、回路の中でダイヤモンド半導体デバイスを動作させなければならない

ダイヤモンド電極金属とプリント基板間を特別な方法でワイヤボンディング

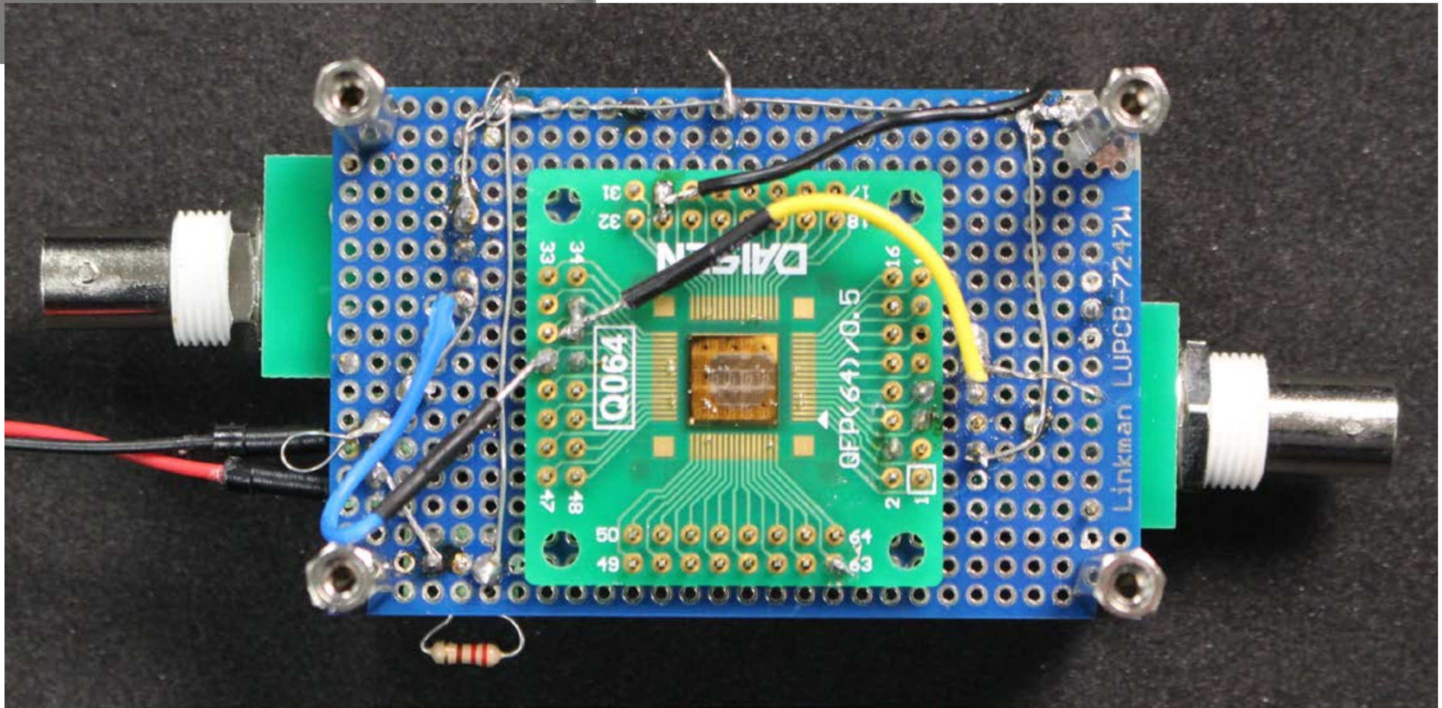


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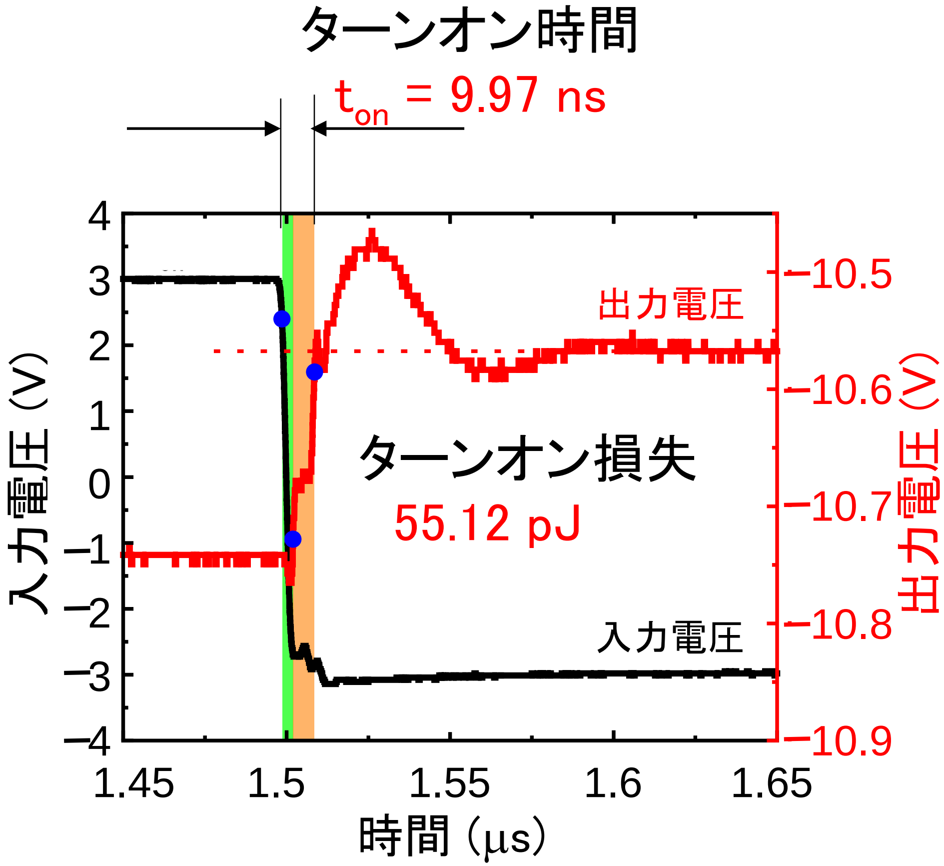
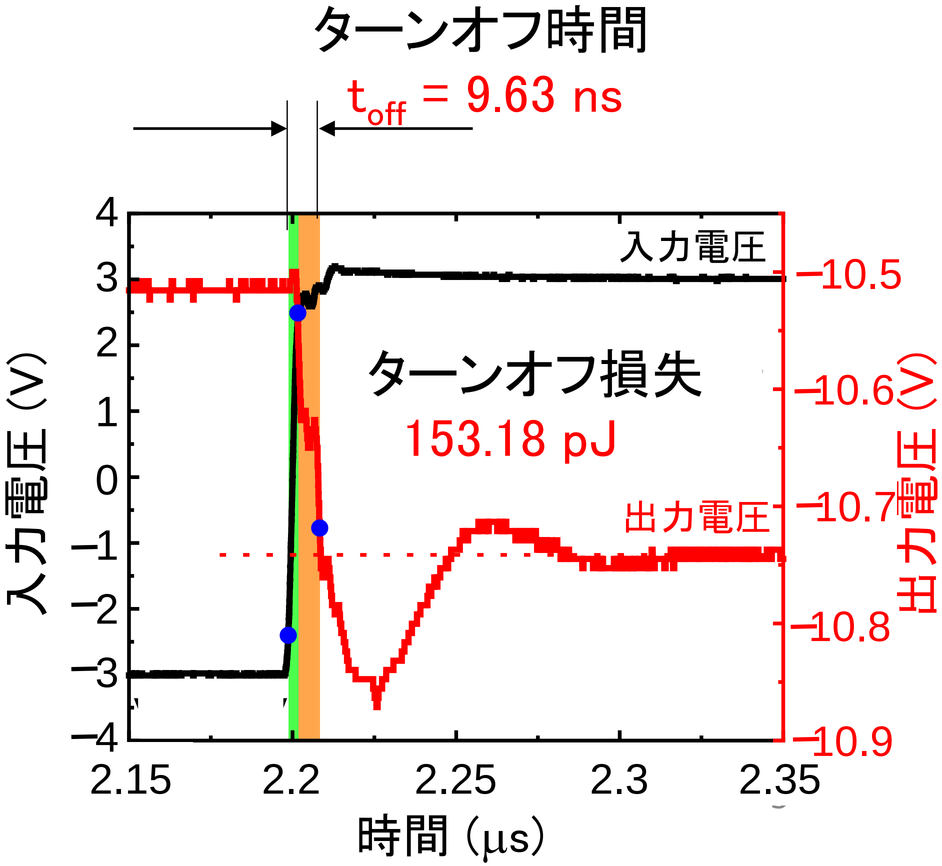
図４． 技術ポイント(2) 10ナノ秒を切る高速のスイッチング動作

スイッチング特性（スイッチング時間、損失）は、エネルギー効率に重要


ターンオン時間


ターンオフ時間

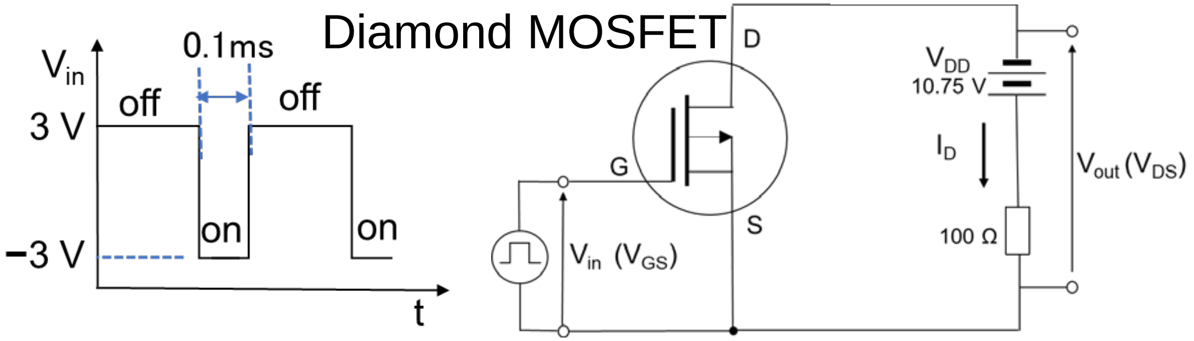
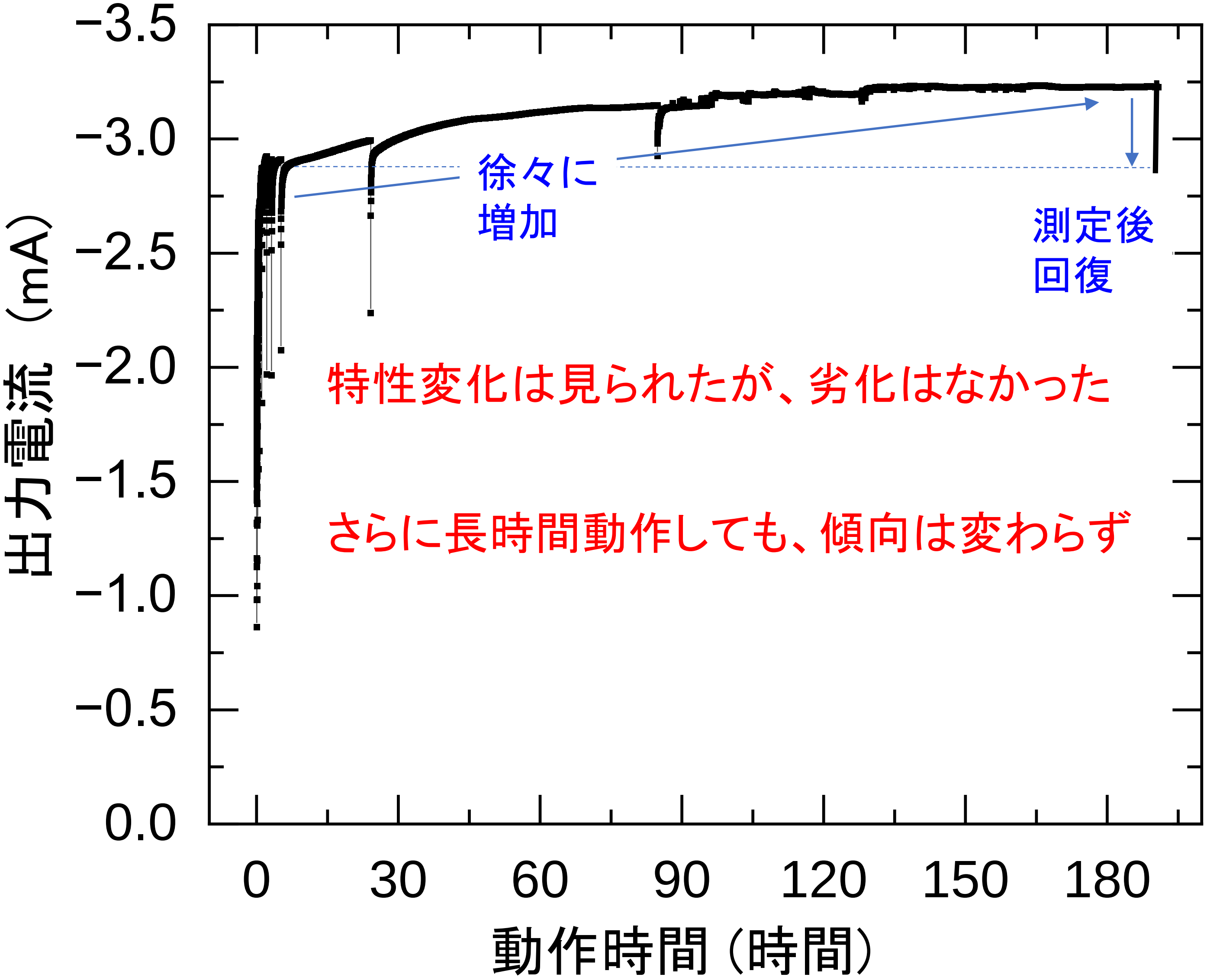


図５．技術のポイント(3) １９０時間の連続動作で特性劣化はなし



徐々に
増加

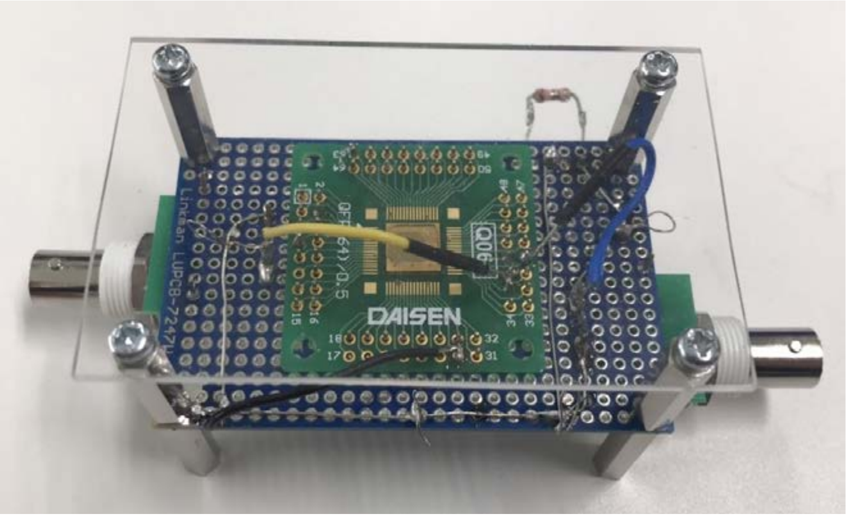
測定後
回復

特性変化は見られたが、劣化はなかった

さらに長時間動作しても、傾向は変わらず

まとめ

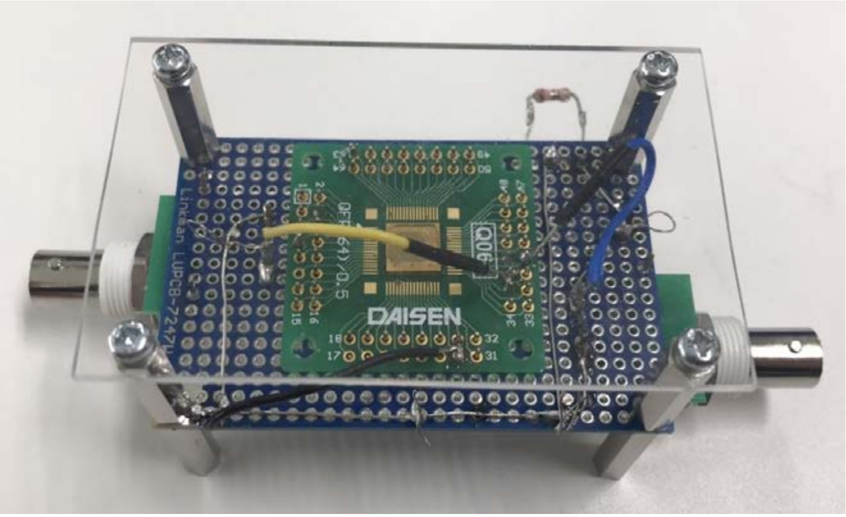
- 究極のパワー半導体物性をもつダイヤモンド半導体
- ダイヤモンド半導体デバイスのパワー回路を開発
- ダイヤモンド半導体パワー回路で10ナノ秒を切る高速スイッチング動作
- ダイヤモンド半導体パワー回路で190時間の連続動作で特性劣化はなし
- Beyond5G携帯基地局および電気自動車電力制御用デバイスに最適



今後の展開

- 開発したダイヤモンド半導体パワー回路で、特性変化の物理的機構を明らかにするとともに、その対策を講じたダイヤモンド半導体デバイスを作製してまいります。

- さらに高電圧での動作や過酷な動的特性試験を行い、実用化を目指した研究開発を加速してまいります。



補足説明　その他のダイヤモンド半導体の用途

【送電用パワー半導体】

- 電圧等の変換ロス少なく高効率
- 高電圧、大電流に対応

（出所：岩本晃一、洋上風力発電）

【制御用パワー半導体】

- スイッチングが早く滑らかに運転制御
- 放熱性が高く小型化、軽量化

（出所：川辺謙一、燃料電池自動車のメカニズム）

【6G】

- 高出力、高周波で通信高速化
- 放熱性が高く小型化、省エネ化

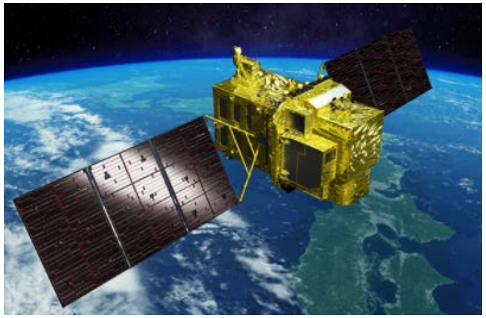
（出所：テック＆サイエンス）

【量子コンピュータ】

- 高出力、高周波で演算が高速化
- 放熱性が高く省エネ化

（出所： Googleの量子コンピュータD-Wave ）

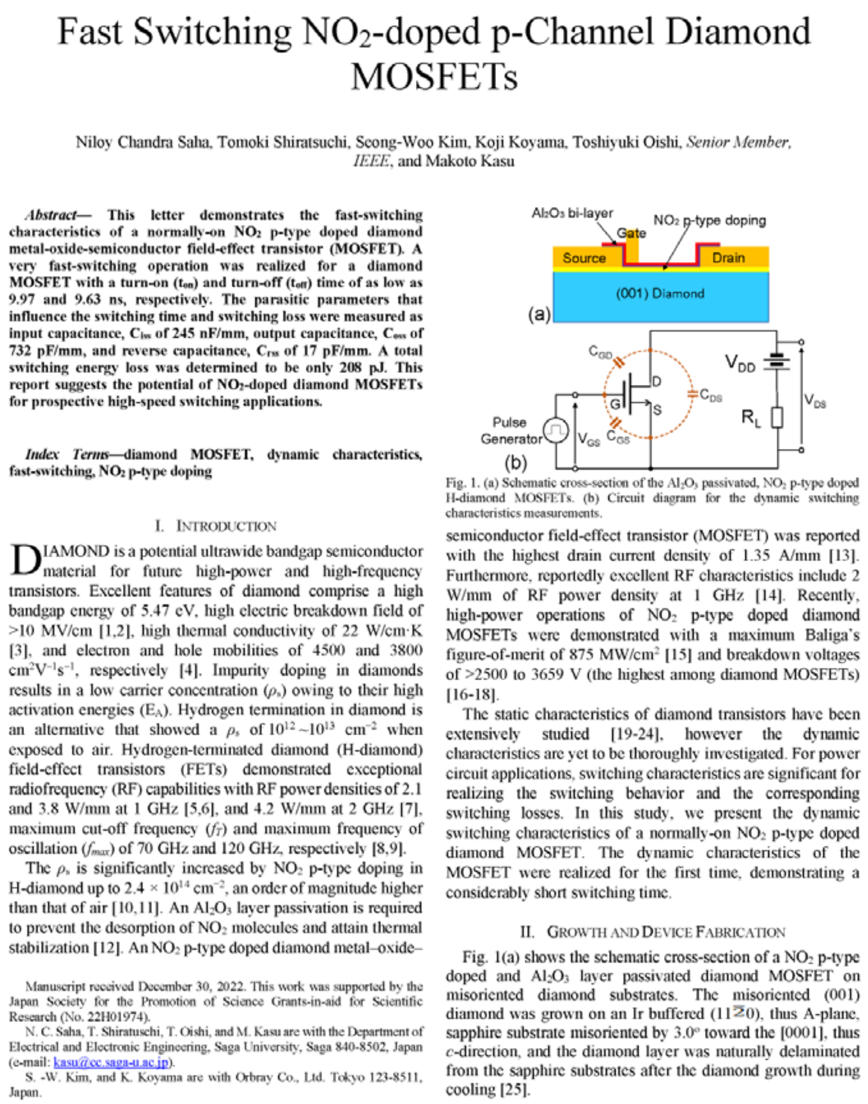
【航空・宇宙】



- 高出力、高周波で演算が高速化
- 放熱性が高く小型化、省エネ化

（出所：JAXAだいち3号HP）

補足説明　掲載論文



Fast Switching NO₂-doped p-Channel Diamond MOSFETs

Niloy Chandra Saha, Tomoki Shiratsuchi, Seong-Woo Kim, Koji Koyama, Toshiyuki Oishi, *Senior Member, IEEE*, and Makoto Kasu

***Abstract*— This letter demonstrates the fast-switching characteristics of a normally-on NO_2 p-type doped diamond metal-oxide-semiconductor field-effect transistor (MOSFET). A very fast-switching operation was realized for a diamond MOSFET with a turn-on (t_{on}) and turn-off (t_{off}) time of as low as 9.97 and 9.63 ns, respectively. The parasitic parameters that influence the switching time and switching loss were measured as input capacitance, C_{iss} of 245 nF/mm, output capacitance, C_{oss} of 732 pF/mm, and reverse capacitance, C_{rss} of 17 pF/mm. A total switching energy loss was determined to be only 208 pJ. This report suggests the potential of NO_2-doped diamond MOSFETs for prospective high-speed switching applications.**

***Index Terms*—diamond MOSFET, dynamic characteristics, fast-switching, NO_2 p-type doping**

I. INTRODUCTION

DIAMOND is a potential ultrawide bandgap semiconductor material for future high-power and high-frequency transistors. Excellent features of diamond comprise a high bandgap energy of 5.47 eV, high electric breakdown field of >10 MV/cm [1,2], high thermal conductivity of 22 W/cm·K [3], and electron and hole mobilities of 4500 and 3800 $cm^2V^{-1}s^{-1}$, respectively [4]. Impurity doping in diamonds results in a low carrier concentration (ρ_s) owing to their high activation energies (E_A). Hydrogen termination in diamond is an alternative that showed a ρ_s of 10^{12}–10^{13} cm^{-2} when exposed to air. Hydrogen-terminated diamond (H-diamond) field-effect transistors (FETs) demonstrated exceptional radiofrequency (RF) capabilities with RF power densities of 2.1 and 3.8 W/mm at 1 GHz [5,6], and 4.2 W/mm at 2 GHz [7], maximum cut-off frequency (f_T) and maximum frequency of oscillation (f_{max}) of 70 GHz and 120 GHz, respectively [8,9].

The ρ_s is significantly increased by NO_2 p-type doping in H-diamond up to 2.4×10^{14} cm^{-2}, an order of magnitude higher than that of air [10,11]. An Al_2O_3 layer passivation is required to prevent the desorption of NO_2 molecules and attain thermal stabilization [12]. An NO_2 p-type doped diamond metal–oxide–semiconductor field-effect transistor (MOSFET) was reported with the highest drain current density of 1.35 A/mm [13]. Furthermore, reportedly excellent RF characteristics include 2 W/mm of RF power density at 1 GHz [14]. Recently, high-power operations of NO_2 p-type doped diamond MOSFETs were demonstrated with a maximum Baliga's figure-of-merit of 875 MW/cm^2 [15] and breakdown voltages of >2500 to 3659 V (the highest among diamond MOSFETs) [16-18].

The static characteristics of diamond transistors have been extensively studied [19-24], however the dynamic characteristics are yet to be thoroughly investigated. For power circuit applications, switching characteristics are significant for realizing the switching behavior and the corresponding switching losses. In this study, we present the dynamic switching characteristics of a normally-on NO_2 p-type doped diamond MOSFET. The dynamic characteristics of the MOSFET were realized for the first time, demonstrating a considerably short switching time.

Fig. 1. (a) Schematic cross-section of the Al_2O_3 passivated, NO_2 p-type doped H-diamond MOSFETs. (b) Circuit diagram for the dynamic switching characteristics measurements.

II. GROWTH AND DEVICE FABRICATION

Fig. 1(a) shows the schematic cross-section of a NO_2 p-type doped and Al_2O_3 layer passivated diamond MOSFET on misoriented diamond substrates. The misoriented (001) diamond was grown on an Ir buffered $(11\bar{2}0)$, thus A-plane, sapphire substrate misoriented by 3.0° toward the [0001], thus *c*-direction, and the diamond layer was naturally delaminated from the sapphire substrates after the diamond growth during cooling [25].

Manuscript received December 30, 2022. This work was supported by the Japan Society for the Promotion of Science Grants-in-aid for Scientific Research (No. 22H01974).

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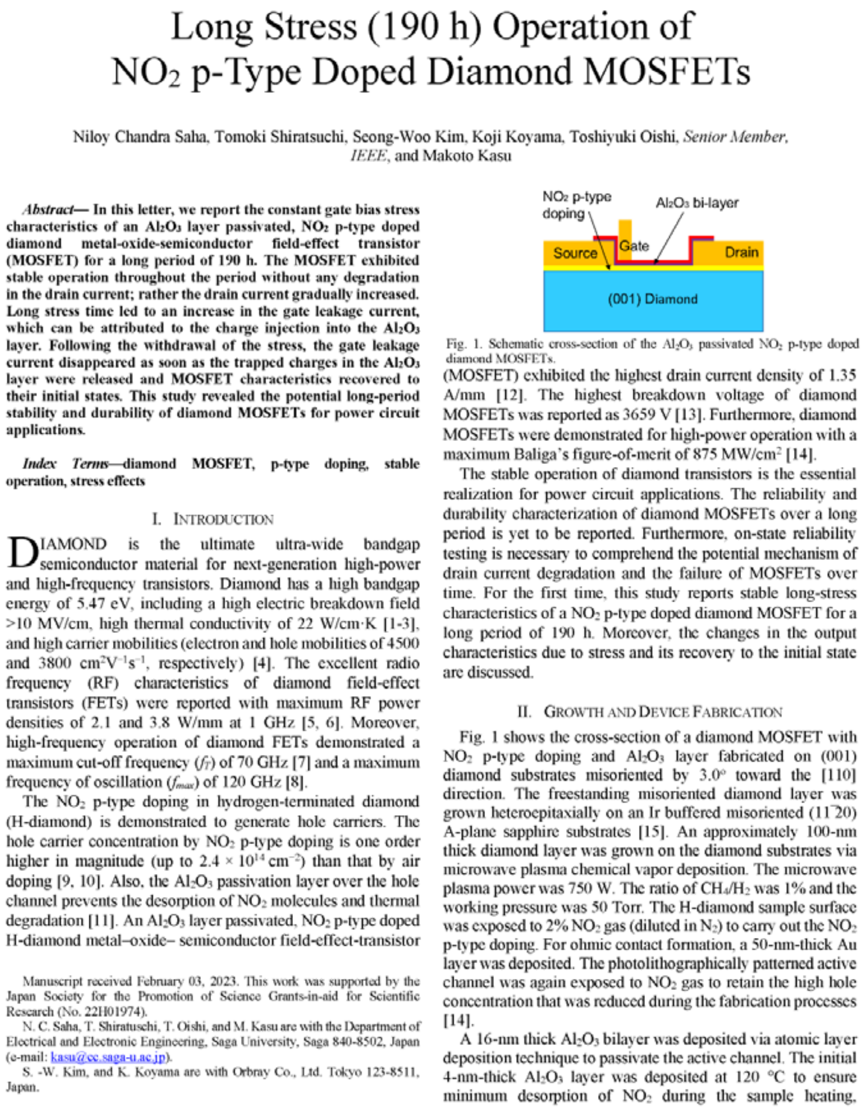

Long Stress (190 h) Operation of NO₂ p-Type Doped Diamond MOSFETs

Niloy Chandra Saha, Tomoki Shiratsuchi, Seong-Woo Kim, Koji Koyama, Toshiyuki Oishi, *Senior Member, IEEE*, and Makoto Kasu

***Abstract*— In this letter, we report the constant gate bias stress characteristics of an Al_2O_3 layer passivated, NO_2 p-type doped diamond metal-oxide-semiconductor field-effect transistor (MOSFET) for a long period of 190 h. The MOSFET exhibited stable operation throughout the period without any degradation in the drain current; rather the drain current gradually increased. Long stress time led to an increase in the gate leakage current, which can be attributed to the charge injection into the Al_2O_3 layer. Following the withdrawal of the stress, the gate leakage current disappeared as soon as the trapped charges in the Al_2O_3 layer were released and MOSFET characteristics recovered to their initial states. This study revealed the potential long-period stability and durability of diamond MOSFETs for power circuit applications.**

***Index Terms*—diamond MOSFET, p-type doping, stable operation, stress effects**

I. INTRODUCTION

DIAMOND is the ultimate ultra-wide bandgap semiconductor material for next-generation high-power and high-frequency transistors. Diamond has a high bandgap energy of 5.47 eV, including a high electric breakdown field >10 MV/cm, high thermal conductivity of 22 W/cm·K [1-3], and high carrier mobilities (electron and hole mobilities of 4500 and 3800 $cm^2V^{-1}s^{-1}$, respectively) [4]. The excellent radio frequency (RF) characteristics of diamond field-effect transistors (FETs) were reported with maximum RF power densities of 2.1 and 3.8 W/mm at 1 GHz [5, 6]. Moreover, high-frequency operation of diamond FETs demonstrated a maximum cut-off frequency (f_T) of 70 GHz [7] and a maximum frequency of oscillation (f_{max}) of 120 GHz [8].

The NO_2 p-type doping in hydrogen-terminated diamond (H-diamond) is demonstrated to generate hole carriers. The hole carrier concentration by NO_2 p-type doping is one order higher in magnitude (up to 2.4×10^{14} cm^{-2}) than that by air doping [9, 10]. Also, the Al_2O_3 passivation layer over the hole channel prevents the desorption of NO_2 molecules and thermal degradation [11]. An Al_2O_3 layer passivated, NO_2 p-type doped H-diamond metal–oxide– semiconductor field-effect-transistor (MOSFET) exhibited the highest drain current density of 1.35 A/mm [12]. The highest breakdown voltage of diamond MOSFETs was reported as 3659 V [13]. Furthermore, diamond MOSFETs were demonstrated for high-power operation with a maximum Baliga's figure-of-merit of 875 MW/cm^2 [14].

The stable operation of diamond transistors is the essential realization for power circuit applications. The reliability and durability characterization of diamond MOSFETs over a long period is yet to be reported. Furthermore, on-state reliability testing is necessary to comprehend the potential mechanism of drain current degradation and the failure of MOSFETs over time. For the first time, this study reports stable long-stress characteristics of a NO_2 p-type doped diamond MOSFET for a long period of 190 h. Moreover, the changes in the output characteristics due to stress and its recovery to the initial state are discussed.

Fig. 1. Schematic cross-section of the Al_2O_3 passivated NO_2 p-type doped diamond MOSFETs.

II. GROWTH AND DEVICE FABRICATION

Fig. 1 shows the cross-section of a diamond MOSFET with NO_2 p-type doping and Al_2O_3 layer fabricated on (001) diamond substrates misoriented by 3.0° toward the [110] direction. The freestanding misoriented diamond layer was grown heteroepitaxially on an Ir buffered misoriented $(11\bar{2}0)$ A-plane sapphire substrates [15]. An approximately 100-nm thick diamond layer was grown on the diamond substrates via microwave plasma chemical vapor deposition. The microwave plasma power was 750 W. The ratio of CH_4/H_2 was 1% and the working pressure was 50 Torr. The H-diamond sample surface was exposed to 2% NO_2 gas (diluted in N_2) to carry out the NO_2 p-type doping. For ohmic contact formation, a 50-nm-thick Au layer was deposited. The photolithographically patterned active channel was again exposed to NO_2 gas to retain the high hole concentration that was reduced during the fabrication processes [14].

A 16-nm thick Al_2O_3 bilayer was deposited via atomic layer deposition technique to passivate the active channel. The initial 4-nm-thick Al_2O_3 layer was deposited at 120 °C to ensure minimum desorption of NO_2 during the sample heating,

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Manuscript received February 03, 2023. This work was supported by the Japan Society for the Promotion of Science Grants-in-aid for Scientific Research (No. 22H01974).

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補足説明　ダイヤモンド半導体デバイスの高性能化