ダイヤモンド半導体パワーデバイスの出力電力・電圧の世界最高値を更新

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小山浩司(アダマンド並木精密宝石)、大石敏之（佐賀大）

- 究極のパワー半導体物性をもつダイヤモンド半導体
- 世界最大の大口径（2インチ）のダイヤモンドウェハ結晶の製造技術
- 原子レベルダイヤモンド表面のCMP研磨技術
- 世界最高の高出力電力875MW/cm^2、高電圧2568Vの動作
- 宇宙空間の人工衛星の基地局の送信デバイスに最適

N. C. Saha, S. –W. Kim, T. Oishi, M. Kasu,
“875-MW/cm^2 Low-Resistance NO_2 p-type Doped Chemical Mechanical Planarized Diamond MOSFETs”,
IEEE Electron Device Letters 43, 5, 777 (2022); DOI; 10.1109/LED.2022.3164603

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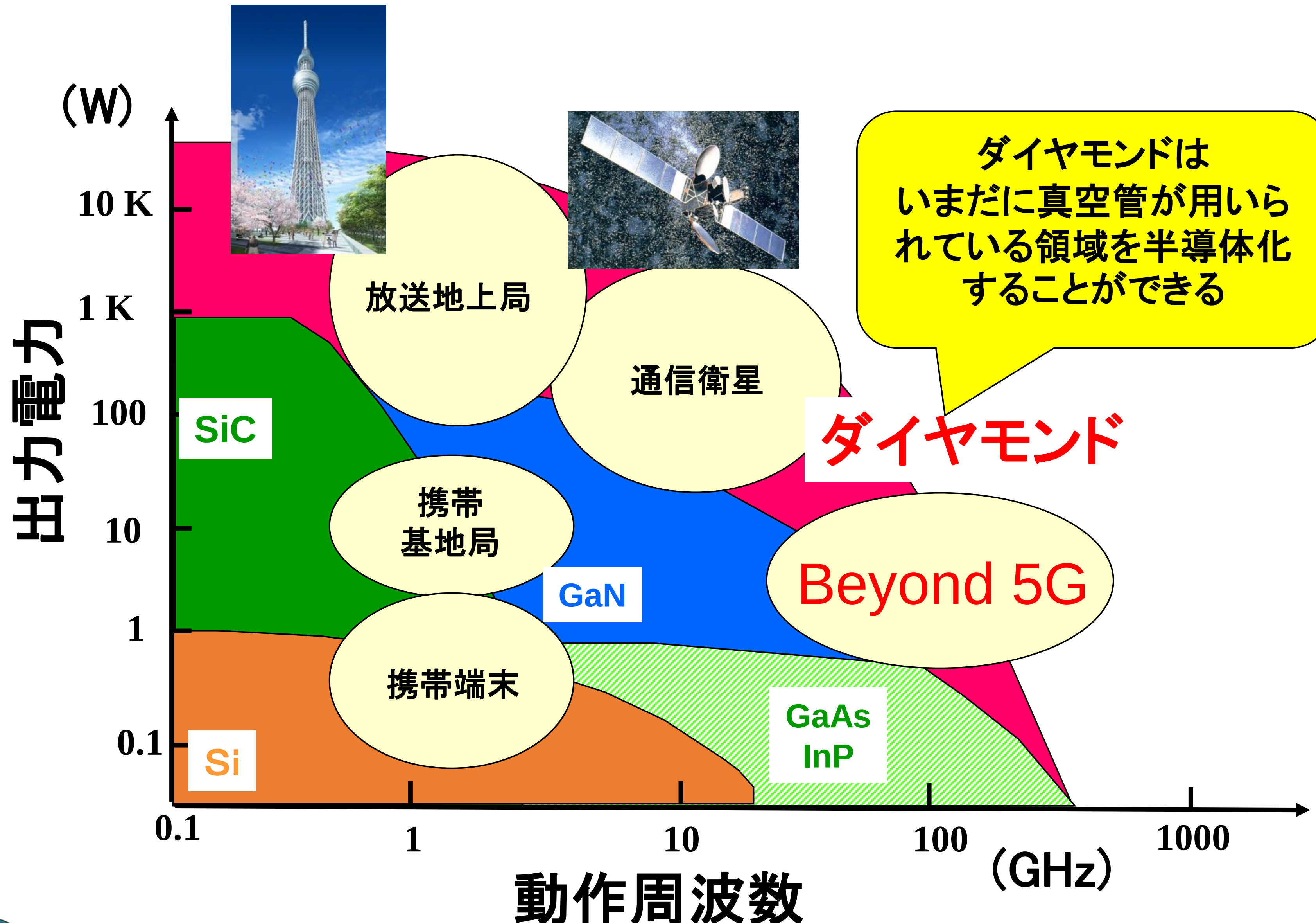
図１． 宇宙やBeyond5Gに向けた半導体の高周波化・高出力化の必要



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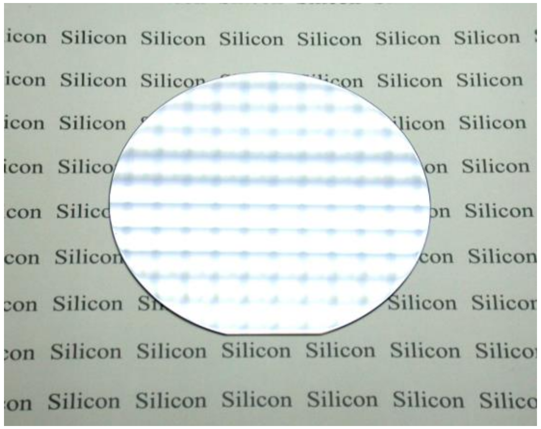
(出所：嘉数、NTT Technical Journal, Vol. 8. No. 8 (2010))

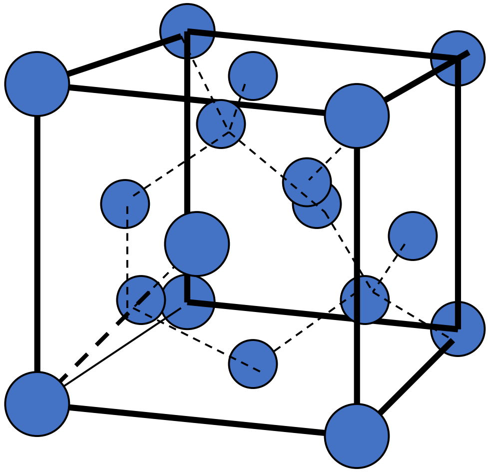
図２．ダイヤモンドの優れた物性から期待されるデバイス性能

ダイヤモンド

シリコン

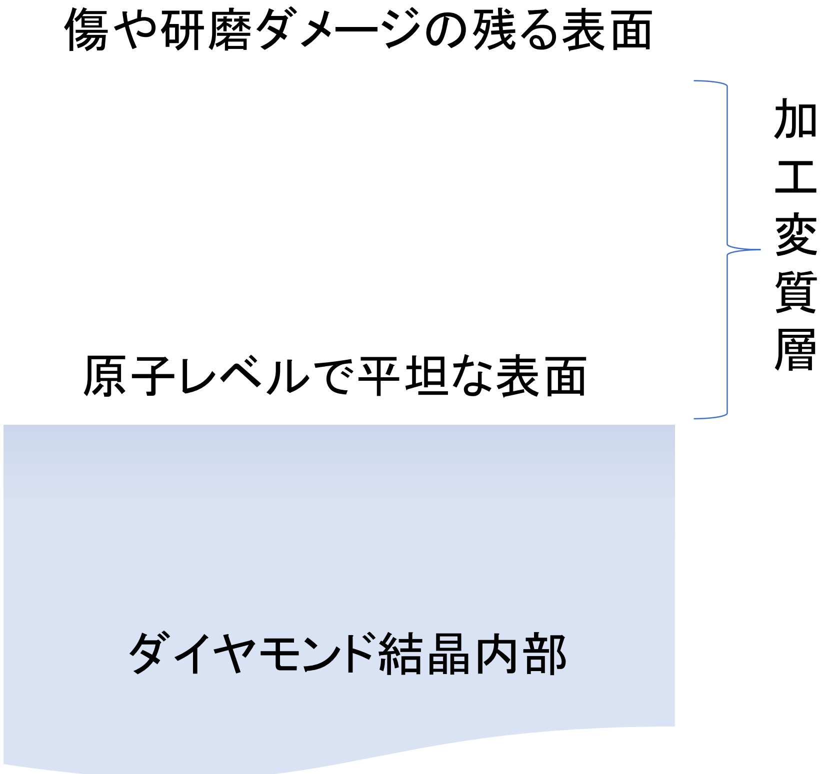


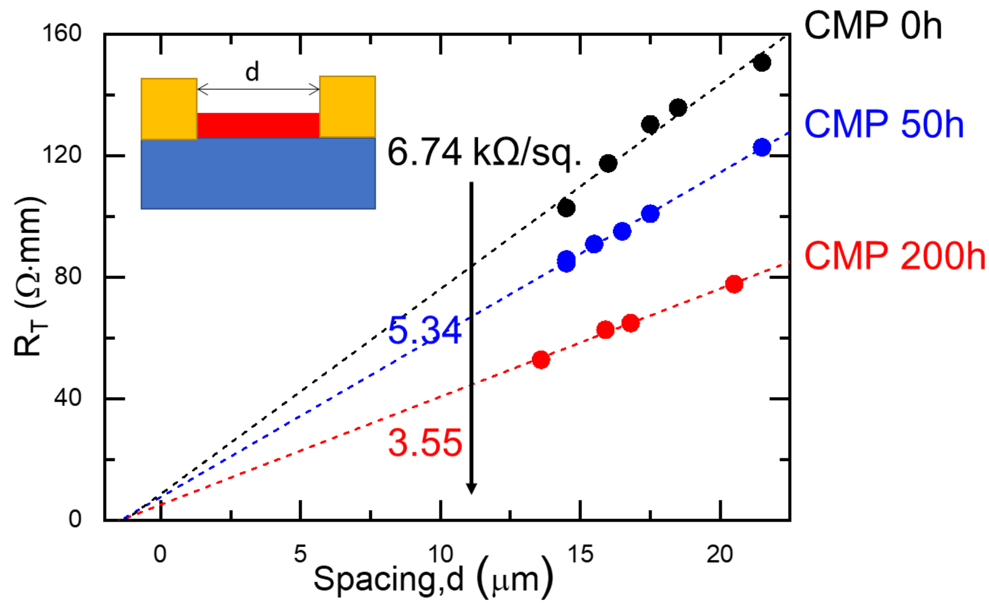
半導体の結晶構造



	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

Chemical Mechanical Planarization
化学機械研磨





K. Koyama et al.,
MRS Spring meeting, Apr. 17–23, 2021.

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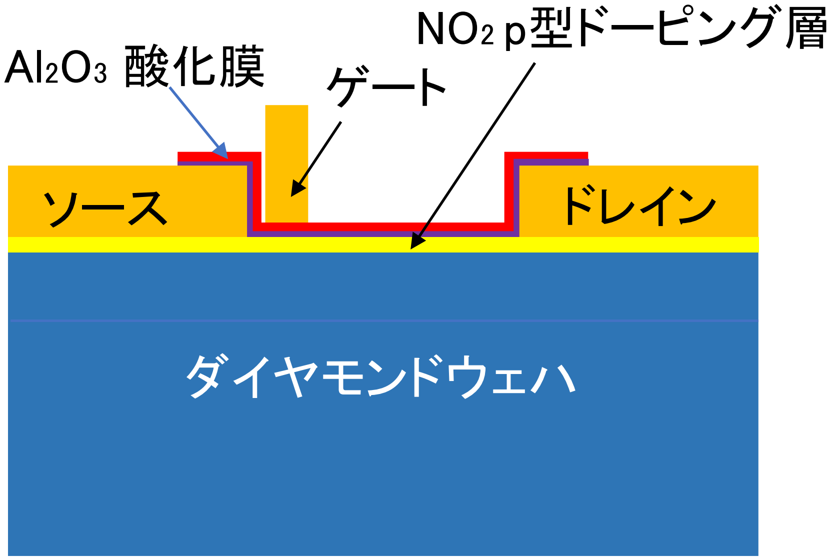
図４　技術ポイント（２）ダイヤモンド半導体デバイスの高性能化



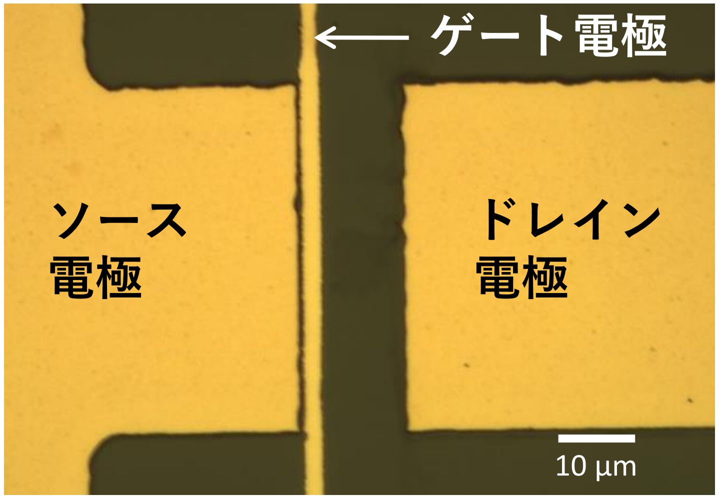
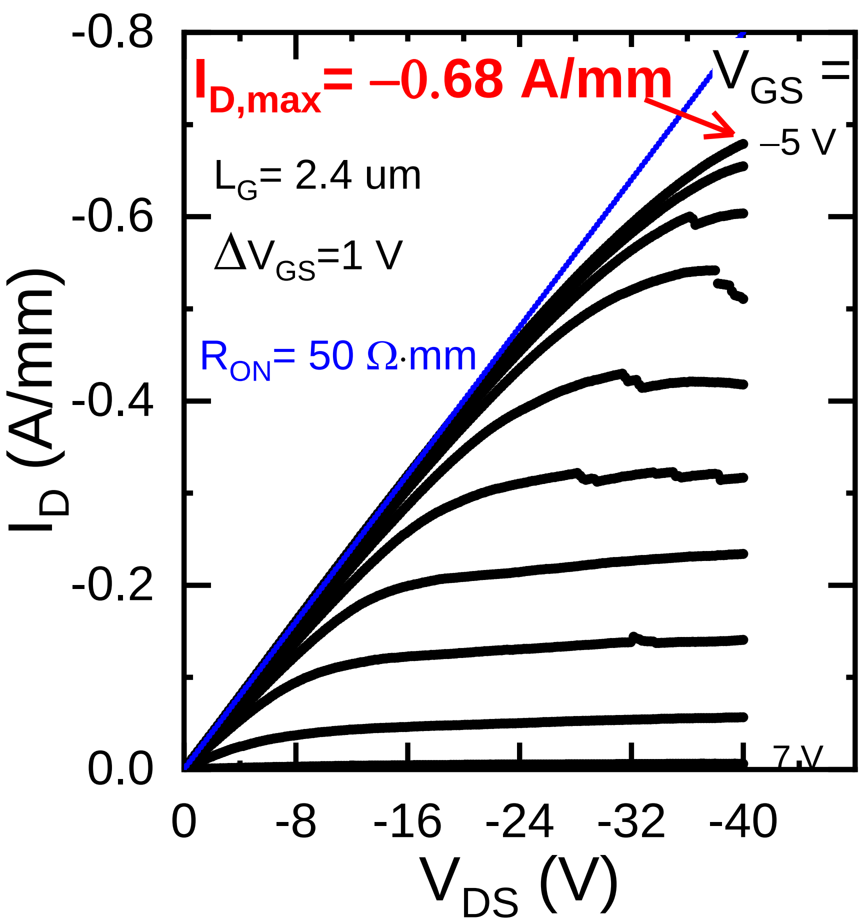


図５　技術ポイント（３）世界最高の出力電力、出力電圧を更新

オン電流 0.68 A/mm



オフ電圧 2568 V

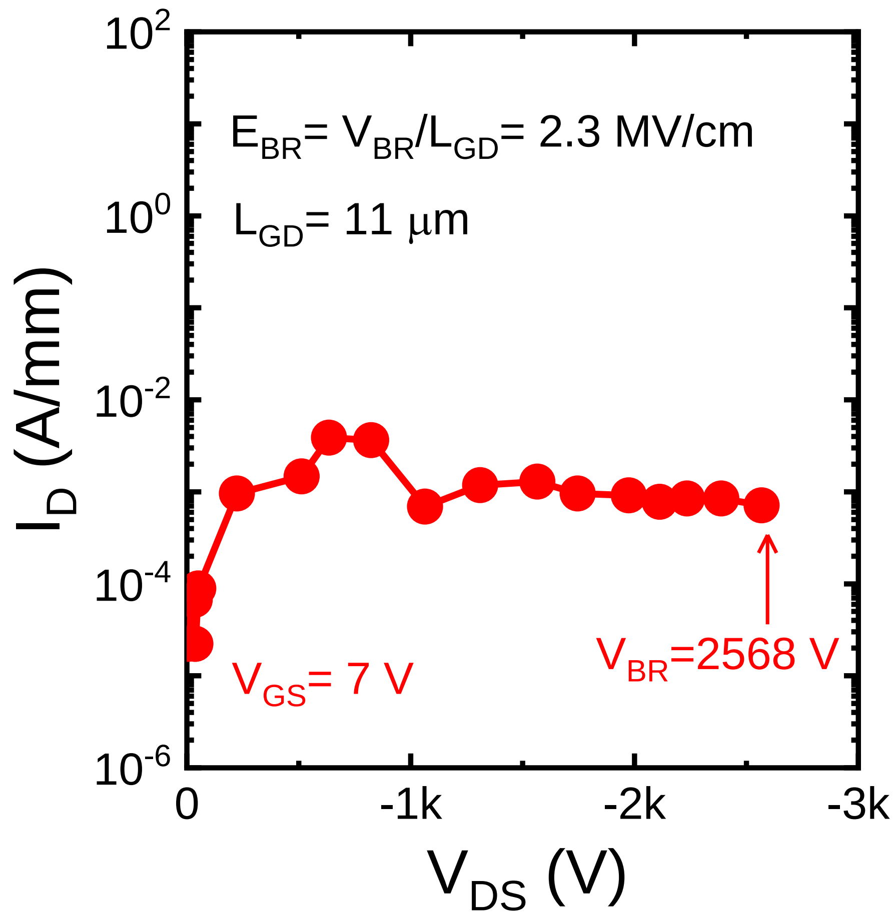


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図５　技術ポイント（３）世界最高の出力電力、出力電圧を更新

世界最高の875 MW/cm²の出力電力値を更新

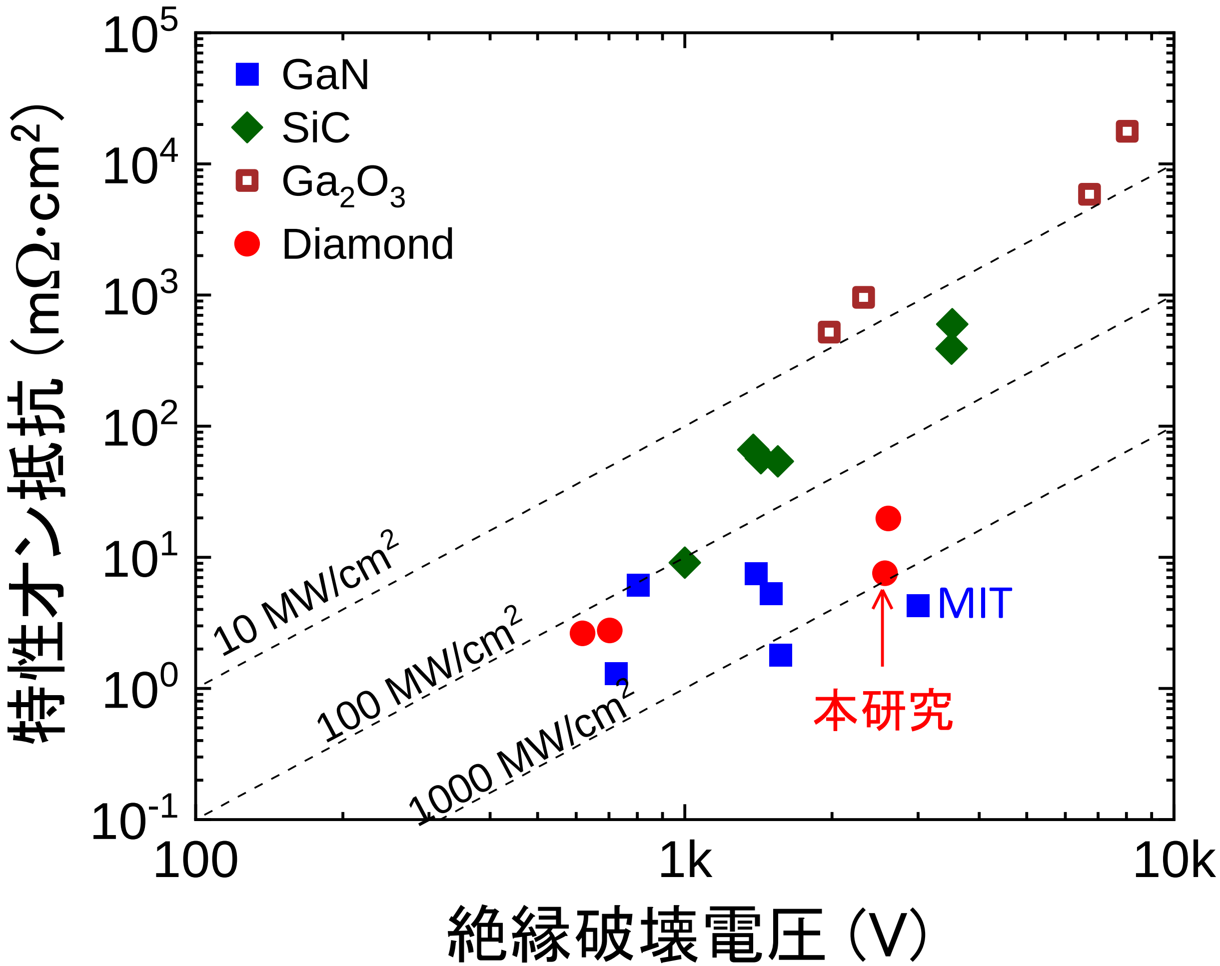

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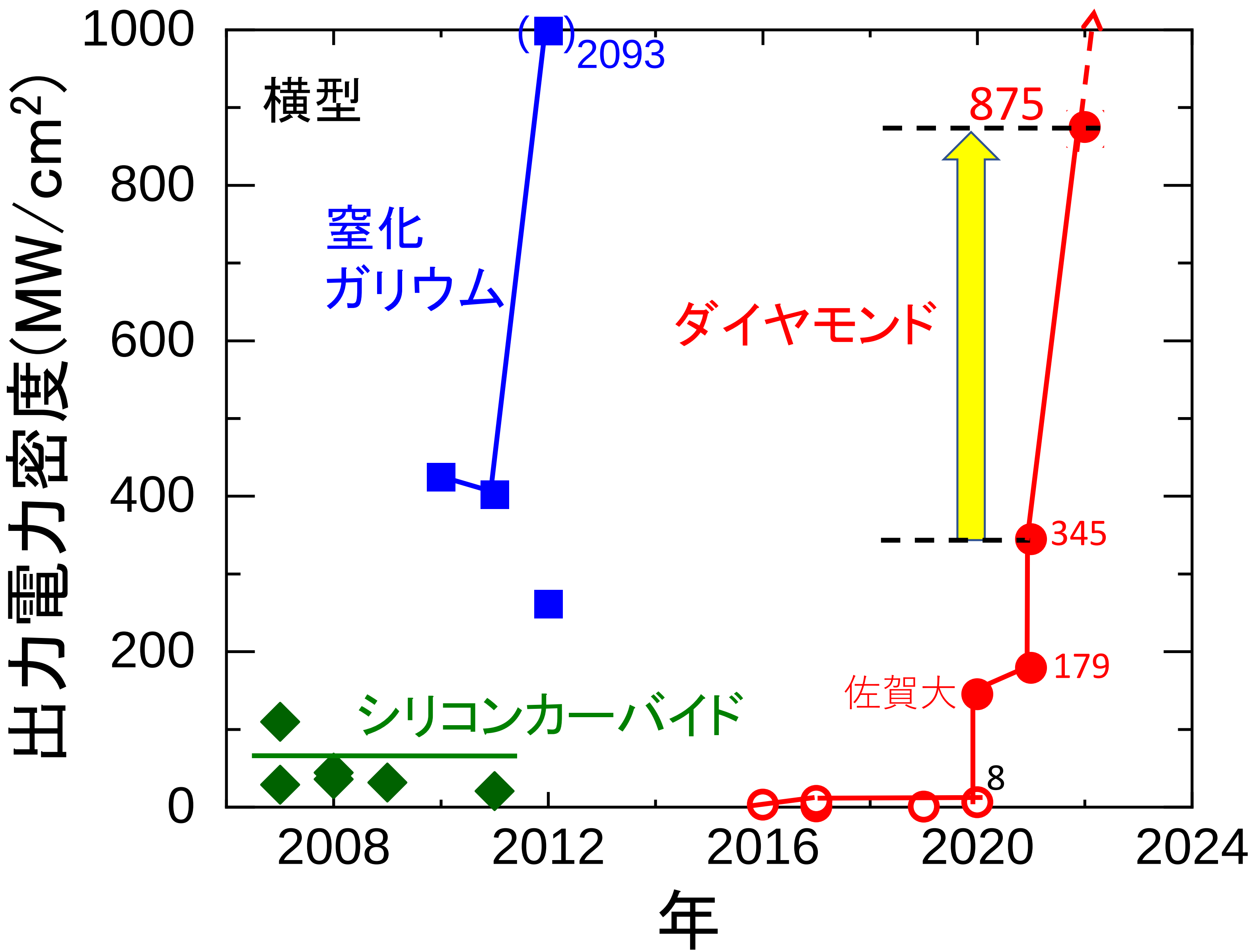
図６　デバイス周辺技術により宇宙衛星用パワー半導体デバイスの実用化



まとめ

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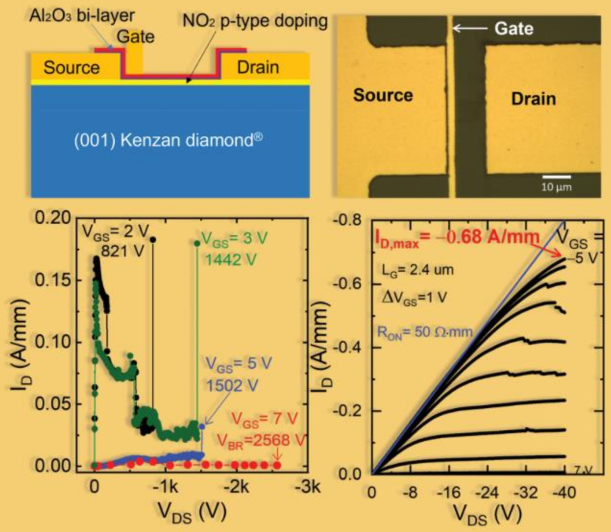
掲載論文

IEEE
ELECTRON DEVICE LETTERS

MAY 2022 VOLUME 43 NUMBER 5 EDLEDZ (ISSN 0741-3106)

MOSFET on Chemical-Mechanical Planarized Heteroepitaxial Diamond



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- Flexible Nanocellulose ITO Device With Solid-State Electrolyte
- Thin-Body Ga_2O_3 Schottky Diode
- Teraherz Power Module Based on 0.34 THz Traveling Wave Tube

A PUBLICATION OF THE IEEE ELECTRON DEVICES SOCIETY IEEE

875-MW/cm^2 Low-Resistance NO_2 p-Type Doped Chemical Mechanical Planarized Diamond MOSFETs

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

***Abstract*—In this study, an Al_2O_3 passivated, NO_2 p-type doped diamond metal–oxide–semiconductor field-effect transistor (MOSFET) was fabricated on a chemical mechanical planarized high-quality heteroepitaxial diamond (Kenzan diamond®) substrate. This MOSFET exhibited a low specific ON-resistance of 7.54 mΩ·cm^2 and a high OFF-state breakdown voltage of −2568 V. The chemical mechanical planarization (CMP) was performed for 200 h on the diamond surface which effectively removed the subsurface damages resulting in a low resistive diamond surface. Thus, the MOSFET showed a high drain current density of −0.68 A/mm and a maximum available power density (Baliga's figure-of-merit) of 874.6 MW/cm^2—the highest reported value for diamond devices.**

***Index Terms*—CMP, diamond MOSFET, heteroepitaxial diamond, high BFOM, NO_2 p-type doping.**

I. Introduction

DIAMOND, with an ultrawide bandgap of 5.47 eV, is the most promising semiconductor material for high-power and high-frequency transistors. It possesses a high breakdown electric field of >10 MV/cm [1], [2] and a thermal conductivity of 22 W/cm·K [3]. Further, undoped diamond exhibits high carrier mobilities (electron and hole mobilities of 4500 and 3800 cm^{2}V^{-1}s^{-1}, respectively) [4]. Hydrogen termination on diamond forms a two-dimensional hole channel, and the hole density and mobility can be controlled by varying the temperature during the hydrogen termination [5]. Hydrogen terminated diamond (H-diamond) field-effect transistors show excellent radiofrequency (RF) characteristics, such as RF power densities of 2.1 and 3.8 W/mm at 1 GHz [6], [7], a maximum cut-off frequency (f_T) of 70 GHz [8], and a maximum oscillation frequency (f_{max}) of 120 GHz [9].

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Digital Object Identifier 10.1109/LED.2022.3164603

NO_2 p-type doping is used in H-diamond to increase the hole carrier concentration (p_s), which can be reportedly increased by one order of magnitude (up to ∼ 2.4 × 10^{14} cm^{-2}) than that in air [10], [11]. An Al_2O_3 layer is used to passivate the hole channel and attain thermal stabilization [12]. Hirama *et al.* [13] demonstrated a diamond metal–oxide–semiconductor field-effect transistor (MOSFET) with the highest drain current density of 1.35 A/mm, using NO_2 doping and an Al_2O_3 layer. Saha *et al.* [14], [15] demonstrated high-drain-current-density and high-breakdown-voltage MOSFETs on heteroepitaxial diamond, which were grown on sapphire substrates using the microneedle technique. One-inch diamond substrates with a low dislocation density (1.4 × 10^7 cm^{-2}) and high crystallinity (113.4 arcsec) were reported as well [16]. Moreover, freestanding diamond with a diameter of 2″ was demonstrated using a step-flow growth on misoriented sapphire [17]. Heteroepitaxial diamond MOSFETs also exhibited the highest lateral breakdown voltage of −2608 V and a Baliga's figure-of-merit (BFOM) of 345 MW/cm^2 [18].

Mechanical polishing, which induces subsurface damages [19], has been widely used on heteroepitaxially grown diamond substrates to obtain a flat surface. To eliminate the subsurface damages and obtain an atomically flat surface, which is desirable for a smoother carrier transport at the heterointerfaces, chemical mechanical planarization (CMP) is applied [20]. In this study, we fabricated NO_2 p-type doped diamond MOSFETs on heteroepitaxial diamond substrates treated using CMP for 200 h. These MOSFETs exhibited very high drain currents, high mobilities, low ON resistances, and high breakdown voltages, and therefore, a high BFOM.

II. Growth and Fabrication

Fig. 1(a) shows the cross-section of the diamond MOSFET fabricated on an 8.0 × 8.0 mm^2 high-quality heteroepitaxial (001) diamond freestanding substrate (Kenzan diamond®). The diamond substrate was grown on sapphire using the microneedle technique and then, treated with CMP for 200 h to remove the mechanical polishing-induced subsurface damages. CMP was performed using the abrasive slurry of Cr_2O_3 at a rotating speed of 3.6 m/s and a pressure of 15 kPa. During the 50 and 200 h of CMP, approximately 90- and 360-μm-thick diamond layers were removed, respectively. As the CMP

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

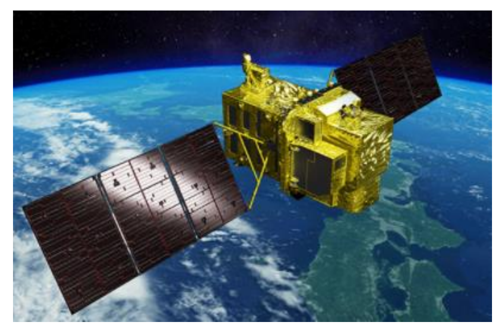
（出所：テック＆サイエンス）

【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】



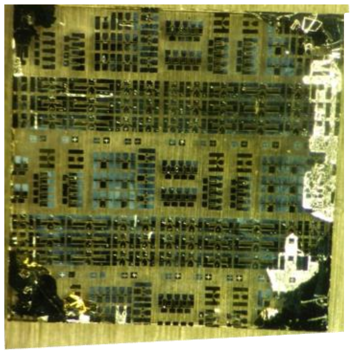
- 高出力、高周波で演算が高速化
- 放熱性が高く小型化、省エネ化

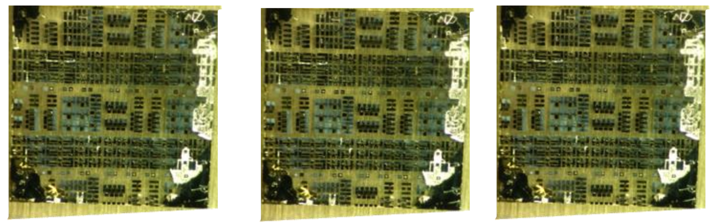
（出所：JAXAだいち3号HP）

補足説明　179　MW/cm²とは？

1cm²角あたり179MW　　（1世帯あたり　50A　5kWとする）

36,000世帯





1cm²角、3つ

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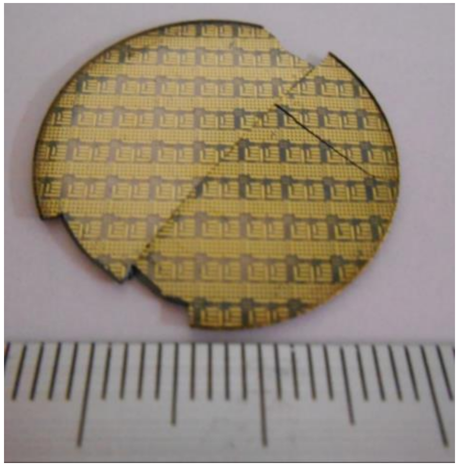
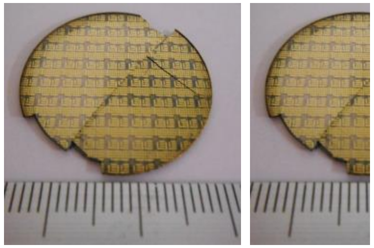
佐賀市
10万世帯

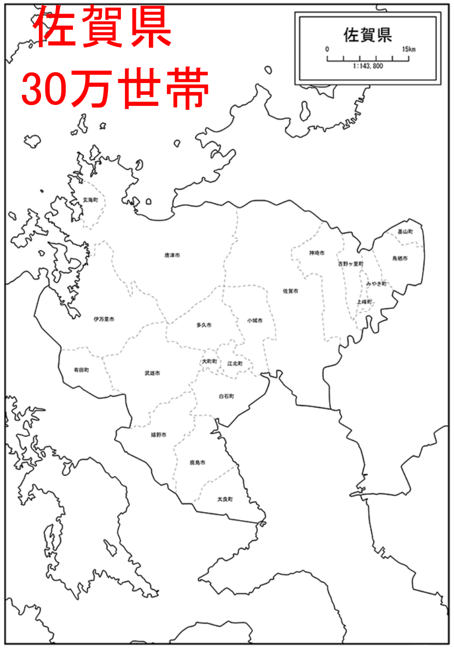
1インチ径あたり1000MW
20万世帯





1インチ径、1枚半

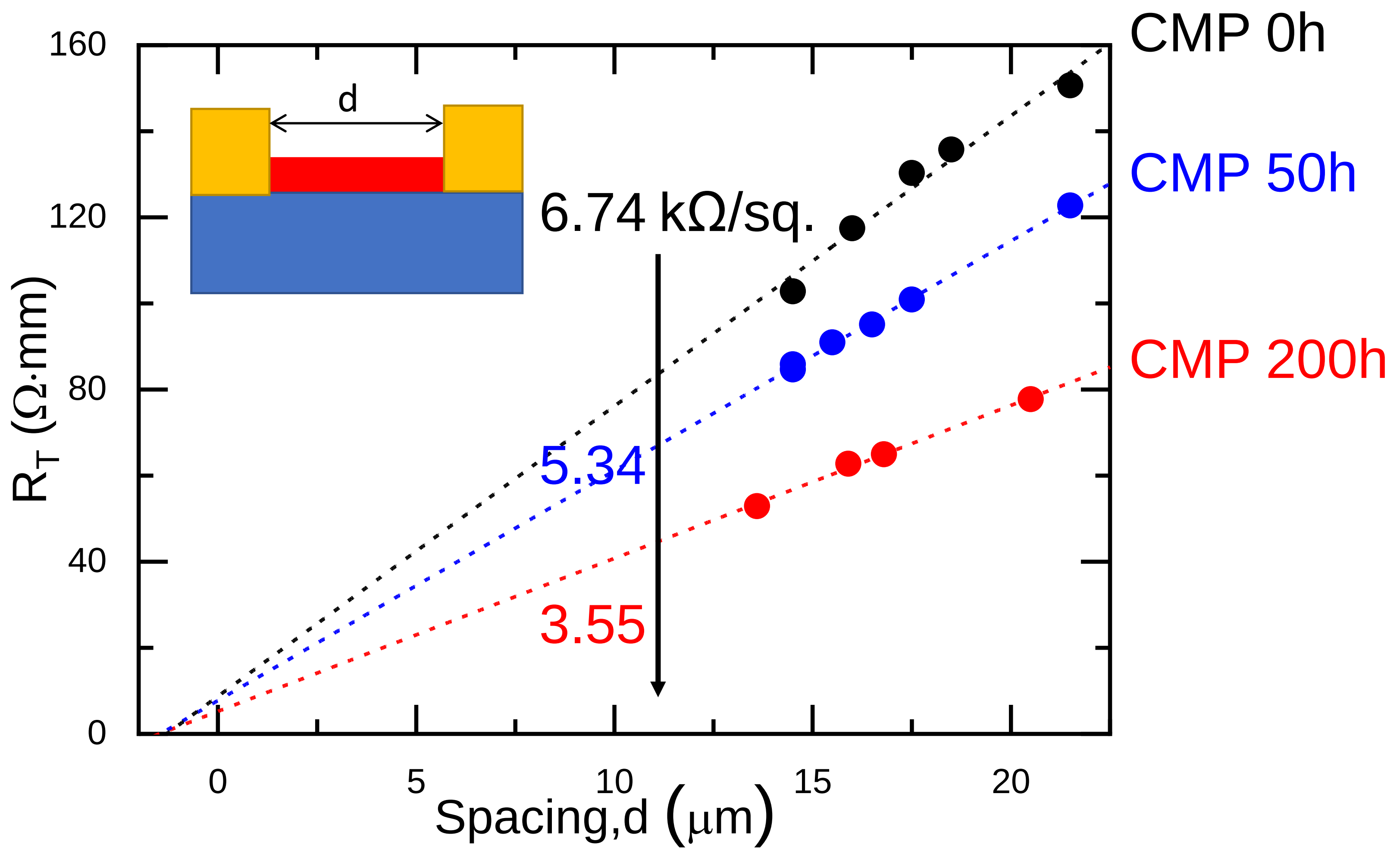
＝



佐賀県
30万世帯

ただし、工場など事業所は考えていません

図4.技術ポイント(1) 原子レベルで平坦なダイヤモンドウェハ結晶の製造技術



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