

Ti/Pt/Au ohmic contacts to β -Ga₂O₃

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ABSTRACT

Low-resistance and thermally stable ohmic contacts are essential for realizing high-performance β -Ga₂O₃ power devices. Although Ti/Au electrodes are widely used as conventional ohmic contacts, Ti–Au interdiffusion during high-temperature annealing remains a critical issue. Introducing a Pt diffusion barrier between Ti and Au is expected to suppress this interdiffusion and improve the thermal stability of the contacts. However, the effectiveness of the Pt layer has not been systematically established through a direct comparison of Ti/Pt/Au and Ti/Au electrodes. In this study, we systematically compared Ti/Pt/Au (30/20/70 nm) and Ti/Au (30/70 nm) ohmic electrodes on (001) β -Ga₂O₃ epiwafers annealed at temperatures (T) ranging from 400 to 600 °C. Both electrode stacks formed ohmic contacts at $T \geq 450$ °C. At $T \geq 500$ °C, however, the Ti/Pt/Au and Ti/Au electrodes exhibited distinctly different behaviors. The Ti/Pt/Au electrodes maintained their layered structures up to $T = 550$ °C and achieved a minimum specific contact resistivity of $(7.17 \pm 1.35) \times 10^{-6} \Omega \text{ cm}^2$ at $T = 550$ °C, whereas the Ti/Au electrodes exhibited severe Ti–Au intermixing at $T \geq 500$ °C and degraded electrical properties, consistent with the cross-sectional scanning transmission electron microscopy observations. This clear contrast demonstrates that the thin Pt layer served as an effective diffusion barrier, thereby improving the thermal stability of the electrodes and enabling higher-temperature annealing to achieve better contact properties.

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I. INTRODUCTION

β -Ga₂O₃ has attracted considerable attention as an emerging ultrawide-bandgap semiconductor for next-generation power devices.¹ Owing to its high estimated breakdown electric field ($\approx 8 \text{ MV cm}^{-1}$),² which exceeds those of SiC and GaN ($\approx 3 \text{ MV cm}^{-1}$), and the availability of large-area bulk substrates and epiwafers up to 6 in.,^{1,3,4} β -Ga₂O₃ is a promising candidate for high-voltage and low-loss power electronic applications, including Schottky barrier diodes (SBDs), field-effect transistors (FETs), and heterojunction p–n diodes with kilovolt-class operation.^{1,5–7}

The formation of low-resistance ohmic contacts is essential for realizing high-performance β -Ga₂O₃ power devices because contact resistance directly contributes to the total on-resistance and conduction loss.^{8,9} Reducing the specific contact resistivity of source, drain, and cathode electrodes is therefore crucial for fully exploiting the material advantages of β -Ga₂O₃.

Ti/Au metal stacks have been widely used as conventional ohmic electrodes since the early stages of β -Ga₂O₃ device development, including SBDs and FETs,^{2,10,11} and have become a *de facto*

standard. During rapid thermal annealing, Ti reduces β -Ga₂O₃ near the interface, potentially increasing the local electron concentration, while being oxidized to form a conductive TiO_x interfacial layer containing multiple Ti oxidation states.^{12,13} These interfacial reactions facilitate carrier transport and enable ohmic contact formation. Meanwhile, Au does not directly contribute to ohmic contact formation but serves as a highly conductive capping layer that protects the highly oxidation-prone Ti layer from oxidation by the surrounding environment and provides a suitable surface for electrical probing and wire bonding. In addition, increasing the local carrier concentration near the contact interface is an effective approach to reducing contact resistivity. Several methods have been reported for this purpose, including regrowth of highly doped layers,^{14,15} plasma treatment,^{2,10} ion implantation,^{16,17} and impurity diffusion from solid sources.¹⁸ Some of these carrier-concentration-enhancement approaches have achieved specific contact resistivities as low as $10^{-6} \Omega \text{ cm}^2$ or lower.^{14–17}

However, Ti/Au electrodes are susceptible to interdiffusion between Ti and Au during high-temperature annealing, which can

degrade their electrical properties. Ti–Au intermixing has been observed by cross-sectional scanning transmission electron microscopy (STEM) after annealing at temperatures ranging from 300 to 520 °C.^{13,19–24} In some reports, Au was found to diffuse through the Ti layer to the β -Ga₂O₃ surface and react with Ga to form GaAu₂, thereby further broadening the reaction region through Ga out-diffusion and Au in-diffusion.¹⁹ These effects restrict the annealing process window and may limit further reductions in the contact resistance. Introducing a diffusion barrier layer between Ti and Au is therefore expected to suppress such interdiffusion.

Among possible diffusion barrier materials, Pt is a promising candidate, as demonstrated by its use in Ti/Pt/Au ohmic contacts to diamond.²⁵ Accordingly, its insertion between Ti and Au is expected to suppress interdiffusion during annealing while preserving the beneficial role of Ti in forming ohmic contacts to β -Ga₂O₃. Ti/Pt/Au ohmic contacts to β -Ga₂O₃ have also been reported.^{26–29} However, the role of the Pt layer as a diffusion barrier has not been investigated, and systematic studies of the annealing-temperature dependence, detailed contact-resistance analysis, and direct comparisons with conventional Ti/Au contacts remain limited. In particular, whether a Pt diffusion barrier can widen the annealing process window and reduce specific contact resistivity has not yet been clarified.

In this study, we systematically investigated Ti/Pt/Au electrodes on n-type β -Ga₂O₃ and directly compared their electrical properties and thermal stability with those of conventional Ti/Au electrodes. The contact properties were evaluated by circular transmission line model (TLM) measurements following rapid thermal annealing at different temperatures. Through this comparison, we demonstrate that the Pt diffusion barrier suppresses electrode degradation at elevated annealing temperatures, thereby widening the annealing process window and enabling a lower specific contact resistivity than that obtained with conventional Ti/Au contacts.

II. EXPERIMENT

Circular TLM measurements were performed using (001) β -Ga₂O₃ epiwafers. The epiwafers consisted of an HVPE-grown, 1.0 μ m-thick Si-doped homoepitaxial layer on a semi-insulating Fe-doped (001) β -Ga₂O₃ substrate. The sheet resistance, resistivity, carrier concentration, and mobility of the Si-doped layer were $1.79 \times 10^2 \Omega \text{ sq}^{-1}$, $1.8 \times 10^{-2} \Omega \text{ cm}$, $5.2 \times 10^{18} \text{ cm}^{-3}$, and $6.7 \times 10^1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, respectively, as determined by Hall-effect measurements using the van der Pauw method.

Ti/Pt/Au and Ti/Au metal stacks with circular TLM geometries were fabricated on the epiwafers using our standard lift-off process. First, the surfaces were treated with hexamethyldisilazane to enhance resist adhesion. A bilayer resist stack consisting of LOR 5A and AZ 5214E was then prepared by sequential spin-coating and baking. Maskless laser lithography (MLA150, Heidelberg Instruments) was used to define the electrode regions in the AZ 5214E layer. During development, the LOR 5A layer was undercut relative to the AZ 5214E layer, producing a cross-sectional profile suitable for the subsequent lift-off process. After ozone descumming for 2 min (UV-1, Samco),³⁰ the samples were

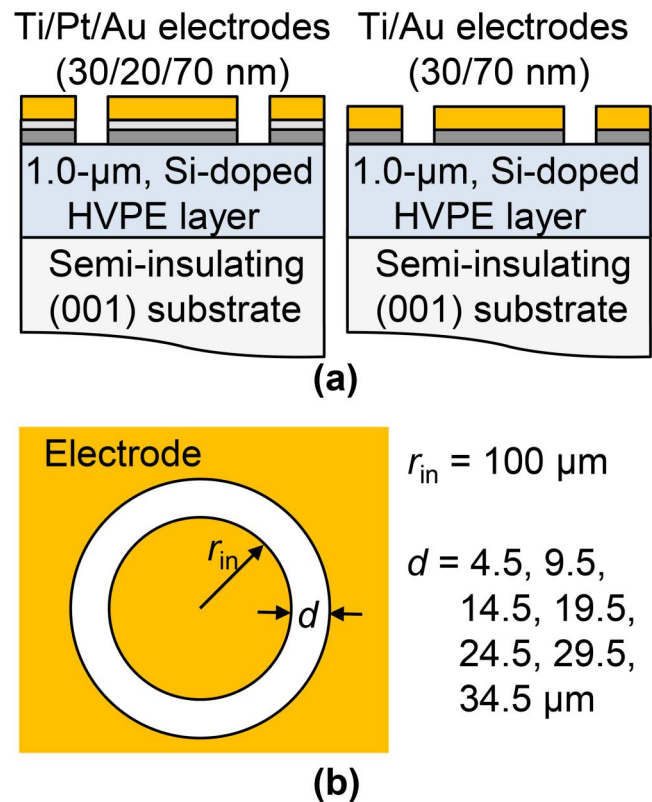


FIG. 1. Schematic illustrations of (a) the cross sections of Ti/Pt/Au and Ti/Au electrode samples and (b) the circular TLM geometry.

immediately introduced into an electron-beam evaporation system (ADS-E86, R-DEC). Ti/Pt/Au (30/20/70 nm) or Ti/Au (30/70 nm) metal stacks were deposited sequentially at rates of 0.2, 0.05, and 0.2 nm/s for Ti, Pt, and Au, respectively. Finally, lift-off was performed in N-methyl-2-pyrrolidone heated to 80 °C, after which the samples were rinsed with isopropyl alcohol and de-ionized water. For both electrode stacks, the radius of the inner electrode (r_{in}) was 100 μ m and the electrode gap widths (d) were 4.5, 9.5, 14.5, 19.5, 24.5, 29.5, and 34.5 μ m. Figures 1(a) and 1(b) schematically show the sample structures and circular TLM geometry, respectively.

After fabrication of the circular TLM electrodes, rapid thermal annealing was performed to enhance carrier transport across the metal–semiconductor interface. Annealing was conducted for 1 min in a lamp-heating system (RTP-6, ADVANCE RIKO) under an N₂ flow of 1.0 slm at atmospheric pressure. The annealing-temperature ranges were 400–600 °C for the Ti/Pt/Au samples and 400–550 °C for the Ti/Au samples. Separate samples were used for each annealing temperature (T). The resulting electrodes were then examined by optical microscopy under identical exposure conditions.

Current–voltage (I – V) measurements were subsequently performed between the inner and outer electrodes of the circular

TLM structures using a manual prober (HMP-400, HiSOL) and a semiconductor parameter analyzer (B1500A, Keysight). For each electrode stack and annealing temperature, one circular TLM set comprising the seven gap widths described above was measured. To minimize parasitic voltage drops in the measurement system, a four-terminal configuration was used: one pair of probes supplied the current, and the other pair measured the voltage across the device. The total resistance (R_t) was obtained from the slope of a linear least-squares fit to all measured data points in each I - V curve.

The R_t of the circular TLM geometry is expressed as^{31,32}

$$R_t = \frac{R_s}{2\pi} \left[\ln\left(\frac{r_{out}}{r_{in}}\right) + \frac{L_t}{r_{in}} \frac{I_0(r_{in}/L_t)}{I_1(r_{in}/L_t)} + \frac{L_t}{r_{out}} \frac{K_0(r_{out}/L_t)}{K_1(r_{out}/L_t)} \right], \quad (1)$$

where I_0 and I_1 are the modified Bessel functions of the first kind of orders 0 and 1, respectively; K_0 and K_1 are the modified Bessel functions of the second kind of orders 0 and 1, respectively; r_{out} is the inner radius of the outer electrode, given by $r_{out} = r_{in} + d$; L_t is

the transfer length; and R_s is the sheet resistance. The first term represents the contribution of the semiconductor sheet resistance in the gap between the electrodes, whereas the second and third terms represent current transfer beneath the inner and outer electrodes, respectively. Nonlinear fitting of this equation to the measured R_t (d) data yields R_s and L_t . The specific contact resistivity (ρ_c) is then calculated as

$$\rho_c = R_s L_t^2. \quad (2)$$

Cross-sectional STEM (Talos F200X G2, Thermo Fisher Scientific) and energy-dispersive x-ray spectroscopy (EDS) analyses were performed to investigate the microstructures and elemental distributions of the Ti/Pt/Au and Ti/Au electrode stacks on β -Ga₂O₃ after annealing at $T = 550$ °C. This annealing temperature yielded the lowest ρ_c for the Ti/Pt/Au contacts, as discussed later. The STEM specimens, approximately 50 nm thick, were prepared with cross sections parallel to the (010) plane of β -Ga₂O₃ using a focused ion beam (FIB)/scanning electron microscopy system (NX5000, Hitachi High-Tech). The sample surfaces were coated with carbon prior to FIB milling to preserve the surface structures. For the STEM observation, the electron beam was incident along the [010] direction of β -Ga₂O₃, and the acceleration voltage was 200 kV. The characteristic x-ray lines used for elemental analysis were O K α , Ga K α + K β , Ti K α + K β , Au L α + L β , and Pt M α + M β .

III. RESULTS AND DISCUSSION

We first examined the temperature-dependent changes in electrode appearance. Figure 2 shows optical microscopy images of the Ti/Pt/Au and Ti/Au electrodes after annealing. The Ti/Pt/Au electrodes retained a gold-colored surface up to $T = 550$ °C and became uniformly but only slightly grayish at $T = 600$ °C [Fig. 2(a)]. In contrast, the Ti/Au electrodes developed a nonuniform grayish appearance even at $T = 500$ °C and became uniformly dark gray at $T = 550$ °C [Fig. 2(b)]. This contrast suggests that the Pt layer effectively suppressed thermally induced intermixing between Ti and Au.

We next characterized the I - V behavior of the electrodes. Figure 3 shows the measured I - V curves between the inner and outer electrodes for different d values, and Fig. 4 summarizes the corresponding R_t - d dependences. For both electrode stacks, the I - V curves at $T = 400$ °C were slightly nonlinear, indicating insufficient thermal reaction for ohmic contact formation, whereas those at $T \geq 450$ °C were linear, confirming ohmic behavior (Fig. 3). The R^2 values for the linear fits to the I - V curves were >0.996 at $T = 400$ °C and >0.999 at $T \geq 450$ °C. At $T \geq 500$ °C, however, clear differences emerged between the Ti/Pt/Au and Ti/Au electrodes. For Ti/Pt/Au, the d dependence of the I - V curves remained systematic up to $T = 600$ °C, and the overall R_t was lower than that at $T = 450$ °C [Figs. 3(a) and 4(a)]. In contrast, for Ti/Au, the d dependence became less systematic, and the overall R_t increased relative to that at $T = 450$ °C [Figs. 3(b) and 4(b)]. The degradation of the Ti/Au electrodes at $T \geq 500$ °C is likely associated with severe interdiffusion between Ti and Au, consistent with the optical microscopy observations [Fig. 2(b)]. Such interdiffusion

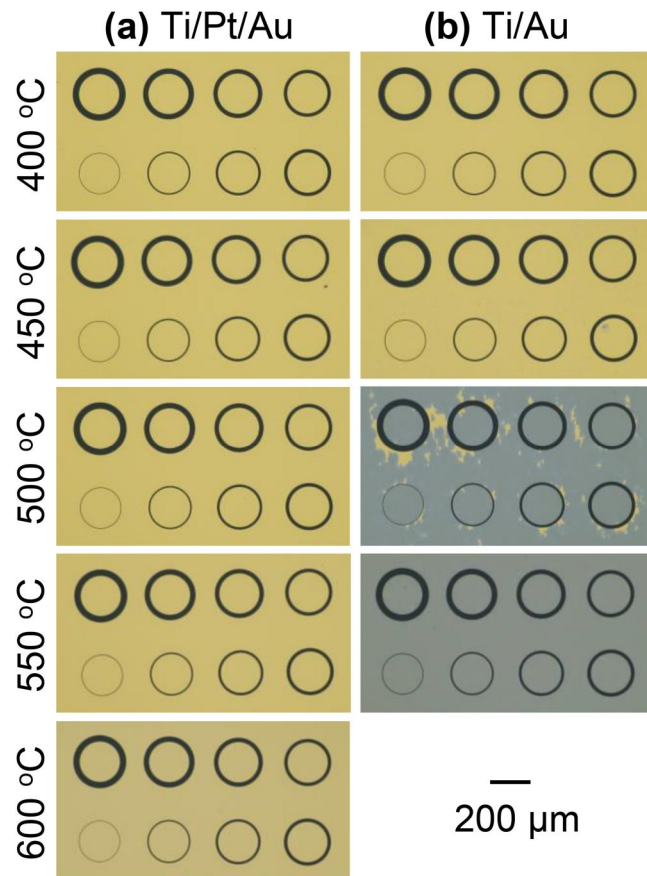


FIG. 2. Optical microscopy images of (a) Ti/Pt/Au and (b) Ti/Au electrodes after rapid thermal annealing at different temperatures.

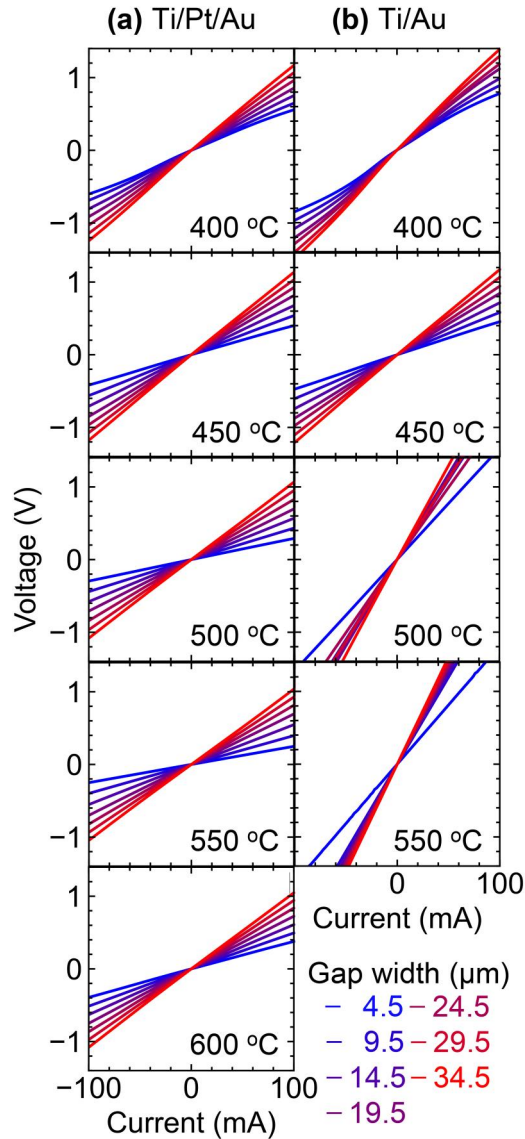


FIG. 3. I - V curves of the annealed (a) Ti/Pt/Au and (b) Ti/Au circular TLM electrodes with different gap widths.

can degrade the contacts and produce an inhomogeneous metal-semiconductor interface.

We then extracted the contact parameters of the electrodes. The R_s and L_t values were determined by nonlinear fitting of the R_t - d dependences to Eq. (1) (Fig. 4), and ρ_c was calculated from these values using Eq. (2), as described in Sec. II. The resulting parameters are shown in Table I and Fig. 5. Note that the contact parameters for the Ti/Au contacts annealed at $T = 500$ and 550 °C are not shown because the corresponding TLM fits were unreliable. The R_s values remained within 167 – 200 Ω sq.⁻¹ [Fig. 5(a)]

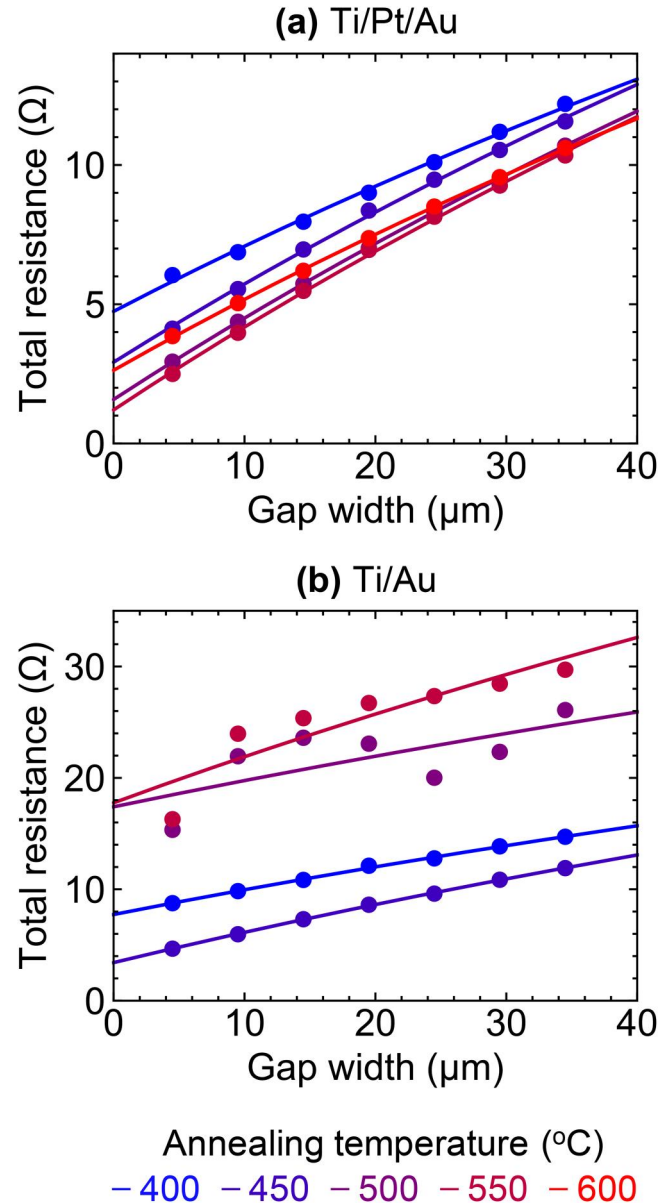


FIG. 4. Total resistance as a function of electrode gap width for the annealed (a) Ti/Pt/Au and (b) Ti/Au electrodes.

and were close to the Hall-measurement value of 1.79×10^2 Ω sq.⁻¹. This agreement indicates that the resistivity of the β -Ga₂O₃ layer was not significantly altered by rapid thermal annealing over the investigated temperature range. Both L_t and ρ_c decreased with increasing T up to 450 °C and were comparable for the two electrode stacks, suggesting that the effect of Ti-Au interdiffusion on the contact properties was less pronounced at this temperature even without the Pt diffusion barrier. At $T \geq 500$ °C,

TABLE I. R^2 values for the circular TLM fits and extracted R_s , L_t , and ρ_c values at different T for Ti/Pt/Au and Ti/Au contacts. R_s , L_t , and ρ_c values for the Ti/Au contacts annealed at $T = 500$ and 550 °C are not shown because the TLM fits were unreliable.

Contact	T (°C)	R^2	R_s (Ω sq. ⁻¹)	L_t (μ m)	ρ_c (Ω cm ²)
Ti/Pt/Au	400	0.996	167.5 $\pm$ 3.9	8.87 $\pm$ 0.43	(1.32 $\pm$ 0.10) $\times 10^{-4}$
	450	0.998	193.7 $\pm$ 3.1	4.73 $\pm$ 0.24	(4.33 $\pm$ 0.37) $\times 10^{-5}$
	500	>0.999	197.5 $\pm$ 0.5	2.51 $\pm$ 0.03	(1.25 $\pm$ 0.03) $\times 10^{-5}$
	550	0.999	199.8 $\pm$ 3.1	1.89 $\pm$ 0.19	(7.17 $\pm$ 1.35) $\times 10^{-6}$
	600	>0.999	175.5 $\pm$ 1.0	4.70 $\pm$ 0.08	(3.88 $\pm$ 0.11) $\times 10^{-5}$
Ti/Au	400	0.998	167.0 $\pm$ 2.9	14.43 $\pm$ 0.41	(3.48 $\pm$ 0.14) $\times 10^{-4}$
	450	>0.999	189.1 $\pm$ 1.7	5.67 $\pm$ 0.14	(6.08 $\pm$ 0.25) $\times 10^{-5}$
	500	0.461	...	...	...
	550	0.811	...	...	...

however, the electrical behaviors of the two electrode stacks differed markedly. For Ti/Pt/Au, L_t and ρ_c decreased further up to $T = 550$ °C, reaching minimum values of $1.89 \pm 0.19 \mu\text{m}$ and $(7.17 \pm 1.35) \times 10^{-6} \Omega \text{ cm}^2$, respectively, before increasing slightly at $T = 600$ °C. In contrast, R_t markedly increased at $T \geq 500$ °C as shown in Fig. 4(b); consequently, their minimum L_t and ρ_c values of $5.67 \pm 0.14 \mu\text{m}$ and $(6.08 \pm 0.25) \times 10^{-5} \Omega \text{ cm}^2$, respectively, were obtained at $T = 450$ °C. These stack-dependent trends are consistent with the observed changes in electrode appearance and indicate that extensive Ti–Au interdiffusion degraded the contact properties. Thus, the Pt diffusion barrier widened the annealing process window toward higher temperatures and enabled lower L_t and ρ_c values than those achieved with conventional Ti/Au electrodes.

Finally, we examined the cross-sectional structures of the Ti/Pt/Au and Ti/Au electrodes after annealing at $T = 550$ °C by STEM. Under this annealing condition, the Ti/Pt/Au electrodes exhibited their lowest L_t and ρ_c values, whereas the Ti/Au electrodes showed severely degraded contact properties (Figs. 3–5).

Figure 6 shows low-magnification high-angle annular dark-field (HAADF)-STEM images of the (a) Ti/Pt/Au and (b) Ti/Au electrodes. In this imaging mode, regions containing heavier elements appear brighter. The Ti/Pt/Au electrode retained a relatively flat surface [Fig. 6(a)], whereas the Ti/Au electrode developed a rough surface, probably because of severe intermixing between Ti and Au [Fig. 6(b)]. Near the electrode/ β -Ga₂O₃ interface, the Ti/Pt/Au electrode contained a multilayer interfacial region with a total thickness of approximately 40 nm [Fig. 6(a)]. In contrast, the Ti/Au electrode contained only a single interfacial layer approximately 10 nm thick [Fig. 6(b)]. This pronounced structural difference is attributable to the presence or absence of the 20 nm-thick Pt layer.

Figures 7 and 8 show HAADF-STEM images, corresponding STEM-EDS elemental maps, and EDS depth profiles of the Ti/Pt/Au and Ti/Au electrodes, respectively. For the Ti/Pt/Au electrode, the mapped area focused on the complex electrode/ β -Ga₂O₃ interfacial region and therefore did not include the upper portion of the Au layer (Fig. 7). For the Ti/Au electrode, the mapped area covered the full electrode thickness because Ti–Au intermixing

extended throughout the stack and a TiO_x layer was observed near the top surface (Fig. 8). Combined interpretation of these complementary datasets enabled identification of the layer structures and constituent elements within the electrodes and interfacial regions.

For the Ti/Pt/Au electrode, the Pt layer effectively suppressed Ti–Au intermixing (Fig. 7). Consequently, the Ti-containing layers remained confined to the interfacial region, and their total thickness (≈ 40 nm) was greater than that observed for the Ti/Au electrode. At the bottom of this region, corresponding to the initial Ti/ β -Ga₂O₃ interface, Ti reduced β -Ga₂O₃ and formed a compositionally graded TiO_x-Ga₂O_y layer (≈ 10 nm), whose upper portion was inferred to be TiO₂-rich from its strong Ti and O signals and weak Ga signal. During the formation of this TiO₂-rich region, Ga released by the extensive reduction of β -Ga₂O₃ was likely excluded from the region and redistributed toward the upper interfacial region because of its limited incorporation into TiO₂. This redistribution produced a compositionally graded Ti–Ga layer (≈ 10 nm) above the TiO_x-Ga₂O_y layer. Above the Ti–Ga layer was a Ti layer (≈ 10 nm) that appeared largely unaffected by either the overlying Pt or the underlying β -Ga₂O₃. A Pt–Ti layer (≈ 10 nm) was observed above the Ti layer. The relative EDS intensities of Pt and Ti suggest that this layer formed through limited diffusion of Pt into Ti. Above these Ti-containing layers, a Pt layer (≈ 20 nm) remained, followed by the Au layer.

For the Ti/Au electrode, the observed structure suggests that a substantial fraction of Ti diffused into the Au layer, limiting the amount of Ti available for reaction with β -Ga₂O₃ (Fig. 8). Consequently, the only Ti-containing interfacial layer was a TiO_x-Ga₂O_y layer approximately 10 nm thick. No distinct Ti layer remained because Ti had diffused into Au, forming an Au–Ti intermixed layer that constituted most of the electrode thickness. Considering the Ga redistribution observed for the Ti/Pt/Au electrode, this Au–Ti intermixed layer may also have contained a small amount of Ga. A thin TiO_x layer was observed at the top of the Au–Ti intermixed layer and likely formed through the oxidation of the diffused Ti in the ambient atmosphere.

These structural differences provide a possible explanation for the distinct contact-resistance behaviors of the two electrode

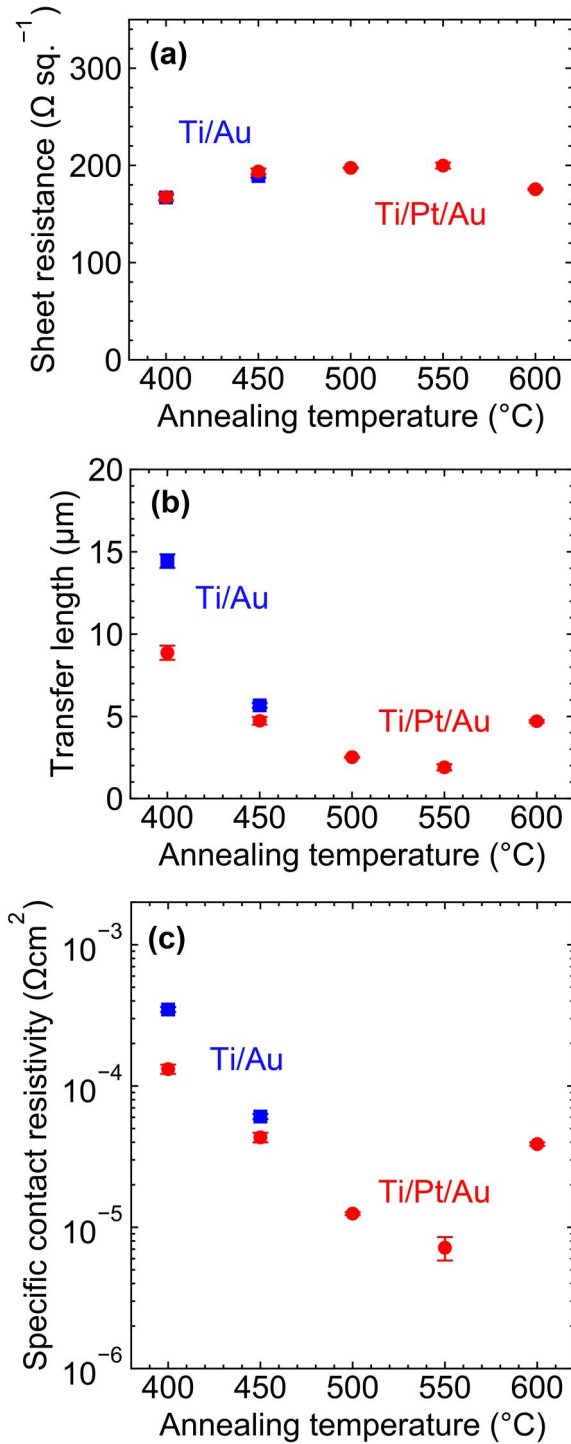


FIG. 5. (a) Sheet resistance, (b) transfer length, and (c) specific contact resistivity as functions of annealing temperature for the Ti/Pt/Au and Ti/Au electrodes. The sheet-resistance data points for the two electrode stacks nearly overlap at 400 $^{\circ}\text{C}$ in (a).

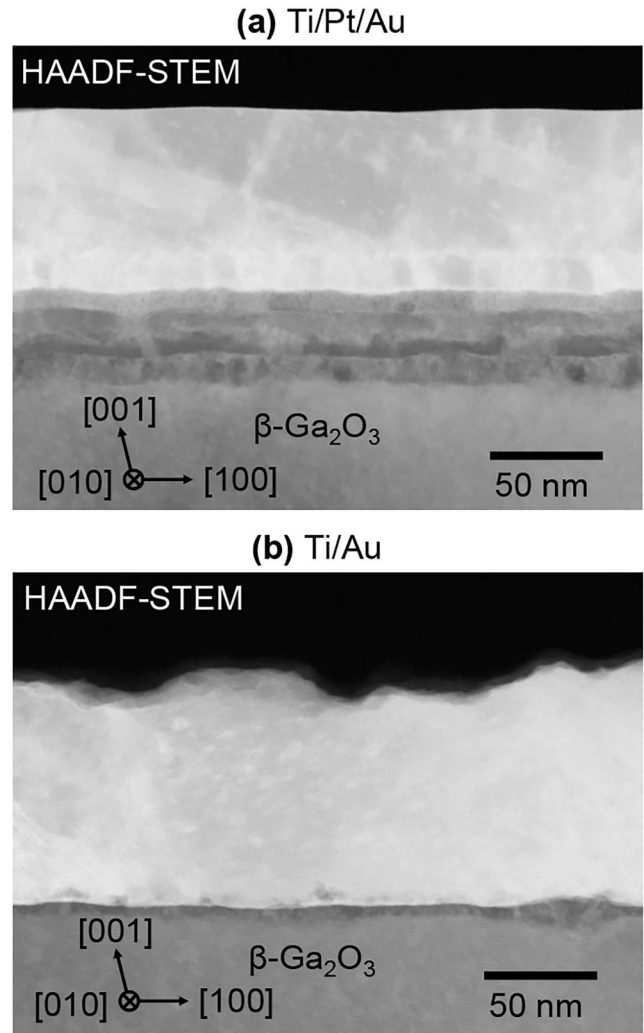


FIG. 6. HAADF-STEM images of the (a) Ti/Pt/Au and (b) Ti/Au electrodes annealed at 550 $^{\circ}\text{C}$.

stacks. In the Ti/Pt/Au electrode, the Pt layer prevented Ti from diffusing into the Au overlayer, allowing a substantial fraction of Ti to remain near the $\beta\text{-Ga}_2\text{O}_3$ interface and participate in interfacial reduction and reaction-layer formation. The resulting $\text{TiO}_x\text{-Ga}_2\text{O}_y$ and Ti-Ga regions may facilitate carrier transport by modifying the interfacial electronic structure and contact barrier. In contrast, extensive Ti-Au intermixing in the Ti/Au electrode depleted Ti from the interface, leaving only a thin $\text{TiO}_x\text{-Ga}_2\text{O}_y$ layer and resulting in degraded and spatially non-uniform contact properties. These observations, therefore, link the improved electrical characteristics of the Ti/Pt/Au electrodes to the preservation of Ti near the $\beta\text{-Ga}_2\text{O}_3$ interface by the Pt diffusion barrier.

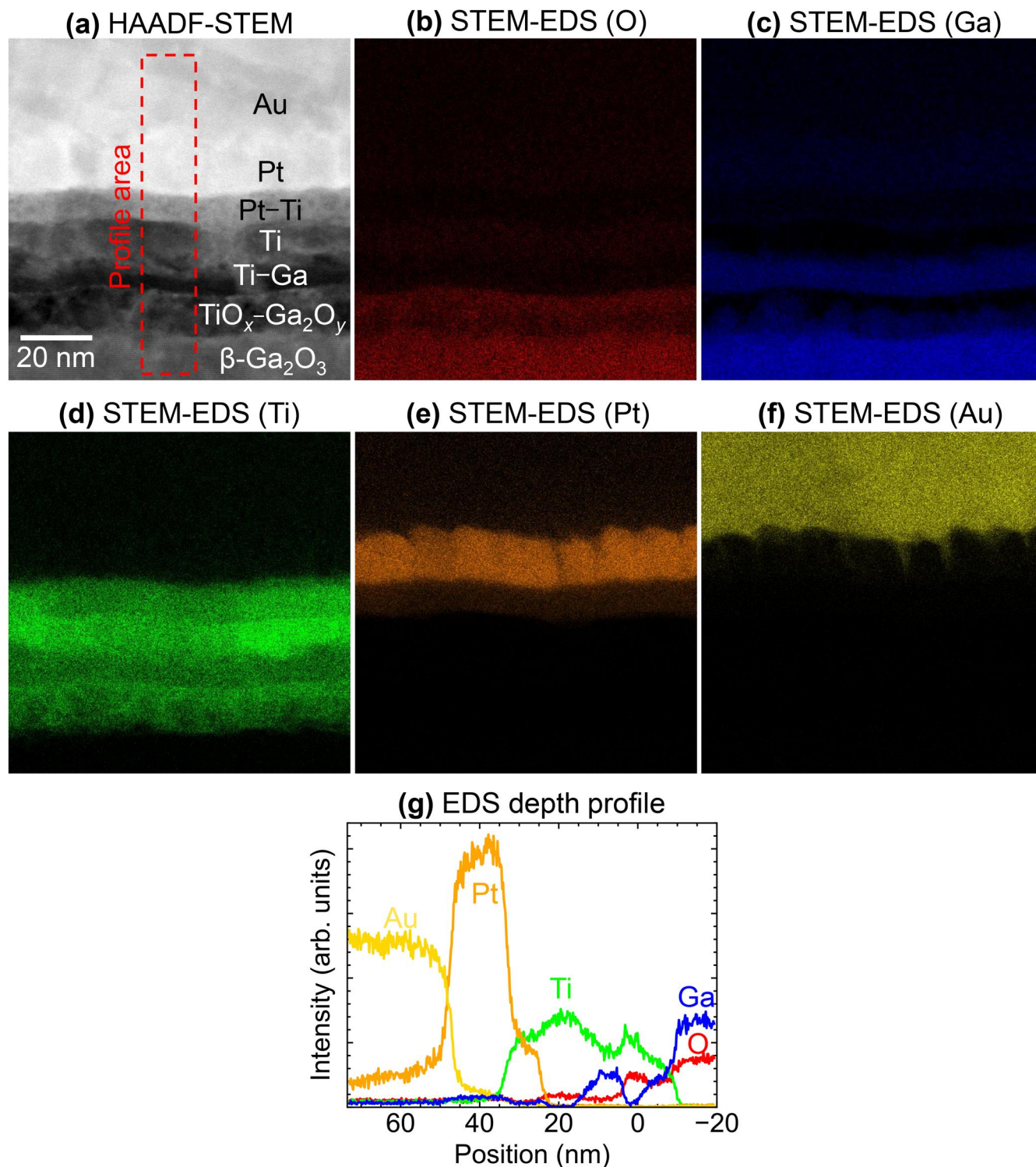


FIG. 7. (a) HAADF-STEM image and (b)–(f) corresponding STEM-EDS elemental maps of the Ti/Pt/Au electrode annealed at 550 °C. (g) EDS depth profile along the profile area in (a).

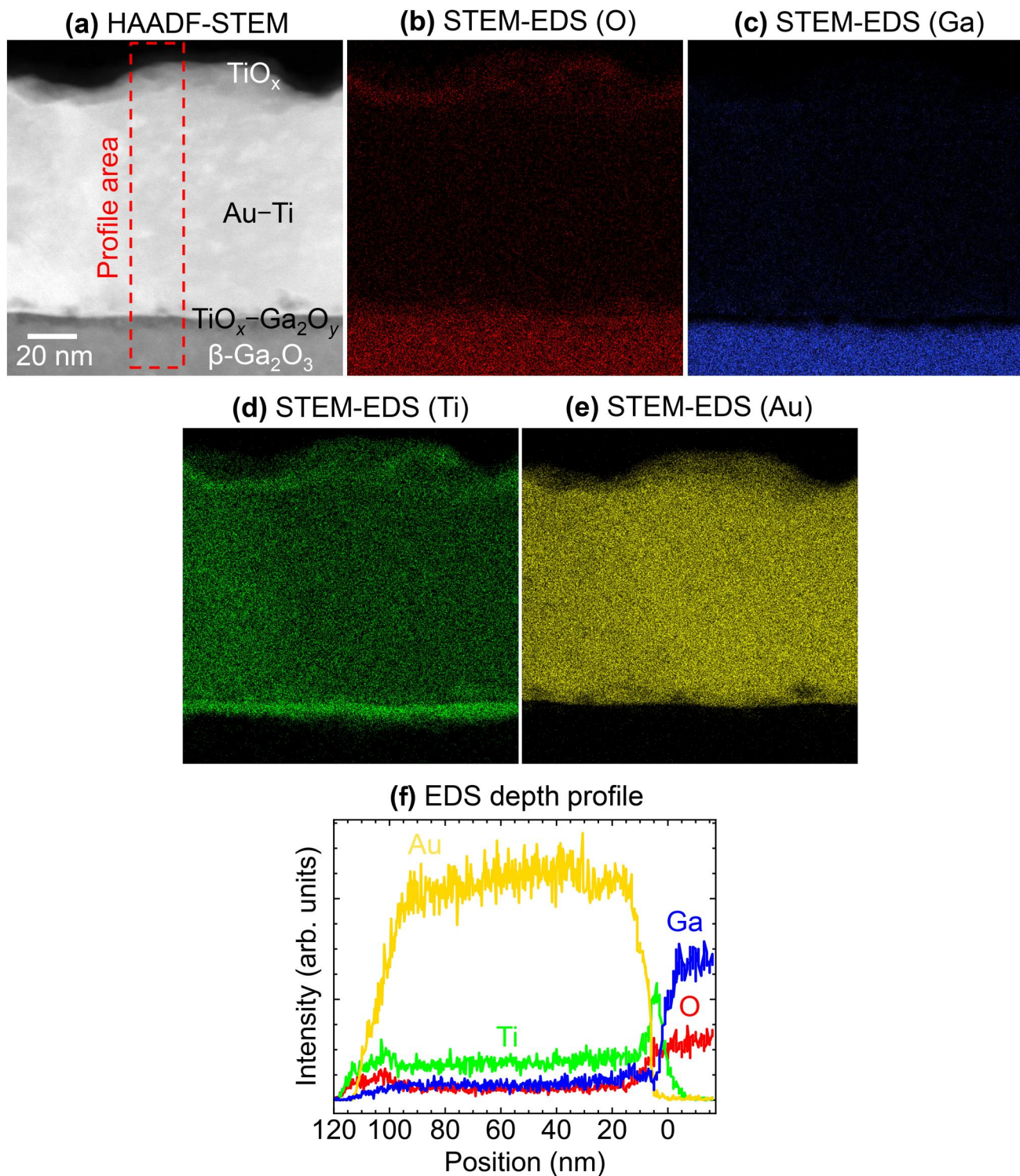


FIG. 8. (a) HAADF-STEM image and (b)–(e) corresponding STEM-EDS elemental maps of the Ti/Au electrode annealed at 550 °C. (f) EDS depth profile along the profile area in (a).

IV. CONCLUSIONS

In conclusion, the direct comparison of Ti/Pt/Au and Ti/Au electrodes clarified the role of the Pt layer in stabilizing Ti-based ohmic contacts to β -Ga₂O₃. The Pt layer suppressed Ti–Au interdiffusion and preserved the Ti-containing reaction near the β -Ga₂O₃ interface, thereby allowing effective contact formation at higher annealing temperatures. The Ti/Pt/Au contact achieved minimum values for L_t of $1.89 \pm 0.19 \mu\text{m}$ and ρ_c of $(7.17 \pm 1.35) \times 10^{-6} \Omega \text{cm}^2$ at 550 °C, whereas corresponding minimum values for Ti/Au were $5.67 \pm 0.14 \mu\text{m}$ and ρ_c of $(6.08 \pm 0.25) \times 10^{-5} \Omega \text{cm}^2$ at 450 °C. These findings demonstrate that Ti/Pt/Au is a promising ohmic electrode for providing a wider annealing process window and improved contact properties in β -Ga₂O₃ power devices.

An important subject for future study is the optimization of the Pt thickness required for effective diffusion-barrier performance under different annealing conditions. In the present study, the 20 nm-thick Pt layer was sufficient to suppress extensive Ti–Au intermixing at $T = 550$ °C, although a limited degree of interdiffusion among the Ti, Pt, and Au layers was observed [Fig. 7(g)]. However, this thickness may not be sufficient at $T = 600$ °C. The electrode surface became slightly grayish [Fig. 2(a)], and R_t , L_t , and ρ_c showed slight degradation [Figs. 4(a), 5(b), and 5(c)]. Although detailed structural information is unavailable because STEM analysis was not performed on the sample annealed at $T = 600$ °C, these observations suggest the interdiffusion may have become more pronounced at 600 °C. Therefore, the Pt thickness required for effective diffusion-barrier performance should be optimized in conjunction with the annealing conditions.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Takayoshi Oshima: Conceptualization (lead); Resources (equal); Writing – original draft (lead). **Yuichi Oshima:** Resources (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- K. Sasaki, *Appl. Phys. Express* **17**, 090101 (2024).
- M. Higashiwaki, K. Sasaki, A. Kuramata, T. Masui, and S. Yamakoshi, *Appl. Phys. Lett.* **100**, 013504 (2012).
- T. Igarashi, Y. Ueda, K. Koshi, R. Sakaguchi, S. Watanabe, S. Yamakoshi, and A. Kuramata, *Phys. Status Solidi B* **262**, 2400444 (2025).
- X. Gao *et al.*, *J. Alloys Compd.* **1063**, 187699 (2026).
- X. Ji *et al.*, *J. Phys. D: Appl. Phys.* **55**, 443002 (2022).
- J. Zhou, X. Zhou, Q. Liu, M. H. Wong, G. Xu, S. Yang, and S. Long, *IEEE Trans. Electron Devices* **71**, 1513 (2024).
- X. Lu, Y. Deng, Y. Pei, Z. Chen, and G. Wang, *J. Semicond.* **44**, 061802 (2023).
- H. Sheoran, V. Kumar, and R. Singh, *ACS Appl. Electron. Mater.* **4**, 2589 (2022).
- L. A. M. Lyle, *J. Vac. Sci. Technol. A* **40**, 060802 (2022).
- T. Oshima, T. Okuno, N. Arai, N. Suzuki, S. Ohira, and S. Fujita, *Appl. Phys. Express* **1**, 011202 (2008).
- K. Sasaki, A. Kuramata, T. Masui, E. G. Villora, K. Shimamura, and S. Yamakoshi, *Appl. Phys. Express* **5**, 035502 (2012).
- J. B. Varley, J. R. Weber, A. Janotti, and C. G. Van de Walle, *Appl. Phys. Lett.* **97**, 142106 (2010).
- M. H. Lee and R. L. Peterson, *APL Mater.* **7**, 022524 (2019).
- A. Bhattacharyya, S. Roy, P. Ranga, D. Shoemaker, Y. Song, J. S. Lundh, S. Choi, and S. Krishnamoorthy, *Appl. Phys. Express* **14**, 076502 (2021).
- F. Alema, C. Peterson, A. Bhattacharyya, S. Roy, S. Krishnamoorthy, and A. Osinsky, *IEEE Electron Device Lett.* **43**, 1649 (2022).
- K. Sasaki, M. Higashiwaki, A. Kuramata, T. Masui, and S. Yamakoshi, *Appl. Phys. Express* **6**, 086502 (2013).
- K. Tetzner *et al.*, *J. Vac. Sci. Technol. A* **41**, 043102 (2023).
- K. Zeng, J. S. Wallace, C. Heimbürger, K. Sasaki, A. Kuramata, T. Masui, J. A. Gardella, and U. Singiseti, *IEEE Electron Device Lett.* **38**, 513 (2017).
- M. H. Lee, T. S. Chou, S. Bin Anooz, Z. Galazka, A. Popp, and R. L. Peterson, *APL Mater.* **10**, 091105 (2022).
- M.-H. Lee, T.-S. Chou, S. Bin Anooz, Z. Galazka, A. Popp, and R. L. Peterson, *ACS Nano* **16**, 11988 (2022).
- C. A. Schettini Mejía, K. Kisslinger, I. Williams, X. Chen, J. C. Yang, and L. M. Porter, *J. Vac. Sci. Technol. A* **44**, 023206 (2026).
- E. V. Favela, H. M. Jeon, K. D. Leedy, K. Zhang, S. W. Tung, F. S. Escobar, C. V. Ramana, and L. M. Porter, *J. Vac. Sci. Technol. B* **41**, 032205 (2023).
- M. H. Lee and R. L. Peterson, *ACS Appl. Mater. Interfaces* **12**, 46277 (2020).
- Y. Yao, R. F. Davis, and L. M. Porter, *J. Electron. Mater.* **46**, 2053 (2017).
- H. A. Hoff, G. L. Waytena, C. L. Vold, J. S. Suehle, I. P. Isaacson, M. L. Rebbert, D. I. Ma, and K. Harris, *Diamond Relat. Mater.* **5**, 1450 (1996).
- F. Alema, Y. Zhang, A. Osinsky, N. Valente, A. Mauze, T. Itoh, and J. S. Speck, *APL Mater.* **7**, 121110 (2019).
- A. Traoré, M. Gouveia, H. Okumura, C. Mannequin, A. Fasson, and T. Sakurai, *Jpn. J. Appl. Phys.* **60**, SBBD15 (2021).
- A. Traoré, H. Okumura, and T. Sakurai, *Jpn. J. Appl. Phys.* **61**, 091002 (2022).
- Y. Jia, S. Sato, A. Traoré, R. Morita, E. Broccoli, F. F. Florena, M. M. Islam, H. Okumura, and T. Sakurai, *AIP Adv.* **13**, 105306 (2023).
- N. Pieczulewski *et al.*, *APL Mater.* **13**, 061122 (2025).
- G. K. Reeves, *Solid-State Electron.* **23**, 487 (1980).
- G. S. Marlow and M. B. Das, *Solid-State Electron.* **25**, 91 (1982).