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Analysis of Trap Centers Generated by Hydrogen Implantation in 4H-SiC Bonded Substrates

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Abstract. In this study, we investigated the generation of trap centers through hydrogen implantation to understand its role in the suppression of forward bias degradation in 4H-silicon carbide (4H-SiC) bonded substrates. During the production of bonded substrates, hydrogen implantation is used for layer splitting. Transmission electron microscopy (TEM) observations revealed that the basal plane dislocation (BPD) in the bonded substrate did not extend into the Shockley-type stacking fault (SSF) and remained stable in the transferred layer below the epitaxial interface even under high forward current stress. Additionally, carrier lifetime, measured using microwave photoconductivity decay (μ-PCD), was considerably reduced by hydrogen implantation. Annealing at 1700°C reduced the implanted hydrogen to levels below the detection limit of secondary ion mass spectrometry (SIMS), yet the carrier lifetime remained short. Deep level transient spectroscopy (DLTS) revealed that, after annealing at 1700°C following hydrogen implantation, the concentration of the $Z_{1/2}$ center increased by more than two orders of magnitude compared to pre-implantation levels. Trap centers, including the $Z_{1/2}$ center, are believed to help prevent forward bias degradation in the bonded substrates by inhibiting the expansion of SSFs in the transferred layer.

Introduction

4H-SiC is a highly promising wide-bandgap material for high-power electrical devices owing to its high dielectric breakdown field and excellent thermal conductivity. In recent years, bonded 4H-SiC substrates have been used in power devices. The SICOXS bonded substrate (SiCkrest™) is produced by bonding a thin monocrystalline SiC layer, less than 1 μm thick, to a low-resistance n-type polycrystalline substrate. This bonded structure offers the advantages of lowering the on-resistance in power devices [1] and mitigating forward bias degradation in PiN diodes [2,3].

Forward bias degradation is commonly observed during 4H-SiC bipolar operation. In PiN diodes, the forward voltage shift increases under forward current stress. This degradation is attributed to the expansion of Shockley-type stacking faults (SSFs) originating from basal plane dislocations (BPDs) [4]. During epitaxial growth, many BPDs are converted into threading edge dislocations (TEDs) [5, 6]. As the forward current density increases, holes can reach the BPDs in the substrate, causing SSFs to expand from these BPDs owing to electron–hole pair recombination, leading to forward bias degradation [7-9]. The proposed driving force behind SSF expansion is the energy gain from electron trapping and carrier recombination in the SSFs [10]. To counteract this issue, techniques such as recombination-enhancing buffer layers, which shorten carrier lifetime, are used to suppress SSF expansion [11]. We have demonstrated that bonded substrates considerably reduce forward bias degradation in PiN diodes, even under high forward current stress [2]. In bonded substrates, forward voltage shifts showed minimal increase, even at a high forward current stress of 1500 A/cm^2. Cross-sectional TEM analysis of the PiN diode revealed that in the transferred layer of the bonded substrate, SSF expansion from BPDs was effectively prevented, even under high forward current stress [3].

Recently, the effect of hydrogen implantation on suppressing forward bias degradation has attracted attention. Studies have shown that hydrogen implantation can inhibit SSF expansion during forward current stress. The point defects introduced by hydrogen implantation have been reported to restrict dislocation glide motion, thereby preventing SSF expansion [12, 13]. Hydrogen implantation also plays a key role in the fabrication of bonded substrates. The bonded substrate is fabricated by implanting hydrogen ions into a monocrystalline substrate, bonding it to a polycrystalline substrate, and then performing layer splitting. The separated monocrystalline layer becomes the transferred layer, with most of the implanted hydrogen passing through it, while some remains within it. Point defects caused by hydrogen implantation can serve as trap centers, potentially promoting carrier recombination. Because the mechanism behind the suppression of SSF expansion and forward bias degradation in bonded substrates remains unclear, this study focuses on the generation of trap centers by hydrogen implantation to investigate the cause.

Experimental

The analysis methods include transmission electron microscopy (TEM), deep level transient spectroscopy (DLTS), secondary ion mass spectrometry (SIMS), and microwave photoconductive decay (μ-PCD). The bonded substrate was examined using TEM after applying forward current stress of 1500 A/cm^2 to a PiN diode [3]. A vertically tilted cross-sectional TEM was used to clearly visualize the moiré fringes of SSFs, enabling the distinction between SSFs and BPDs.

DLTS measurements were performed to identify the types of trap centers generated by hydrogen implantation. In the transferred layer, which has a high carrier concentration, the depletion layer barely expands and the sensitivity is poor during DLTS measurements. To overcome this, an epitaxial layer with a low carrier concentration was grown on the bonded substrate for analysis. The dopant concentration and thickness of the epitaxial layer were 1×10^{16}/cm^3 and 10 μm, respectively. Hydrogen implantation was performed on these epitaxial layers, followed by annealing at 1700°C for 5 min in argon atmosphere on some samples to assess the effects of high-temperature activation annealing on reducing bonding interface resistance. The hydrogen concentration depth profile was measured using SIMS, while the carrier lifetime was evaluated by μ-PCD. For the DLTS measurements, Schottky barrier diodes with nickel electrodes were formed on the samples.

Results and Discussion

1. Cross-sectional TEM image of bonded substrate after high forward current stress

Fig. 1(a) shows a cross-sectional TEM image of the bonded substrate after applying a high forward current stress of 1500 A/cm^2. The expected BPD state before the stress is depicted in Fig. 1(b), and the BPD expansion after the stress observed in the TEM image is illustrated in Fig. 1(c). The BPD observed originated in the transferred layer and extended into the epitaxial layer during growth. Despite the high forward current stress, the BPD in the transferred layer remained stable and did not expand into the SSF, whereas the BPD in the epitaxial layer expanded into the SSF. In contrast, with a monocrystalline substrate, the SSF expanded by more than 1 μm under forward current stress of 1000 A/cm^2 [3]. These findings suggest that SSF expansion can be effectively prevented in the transferred layer of the bonded substrate.

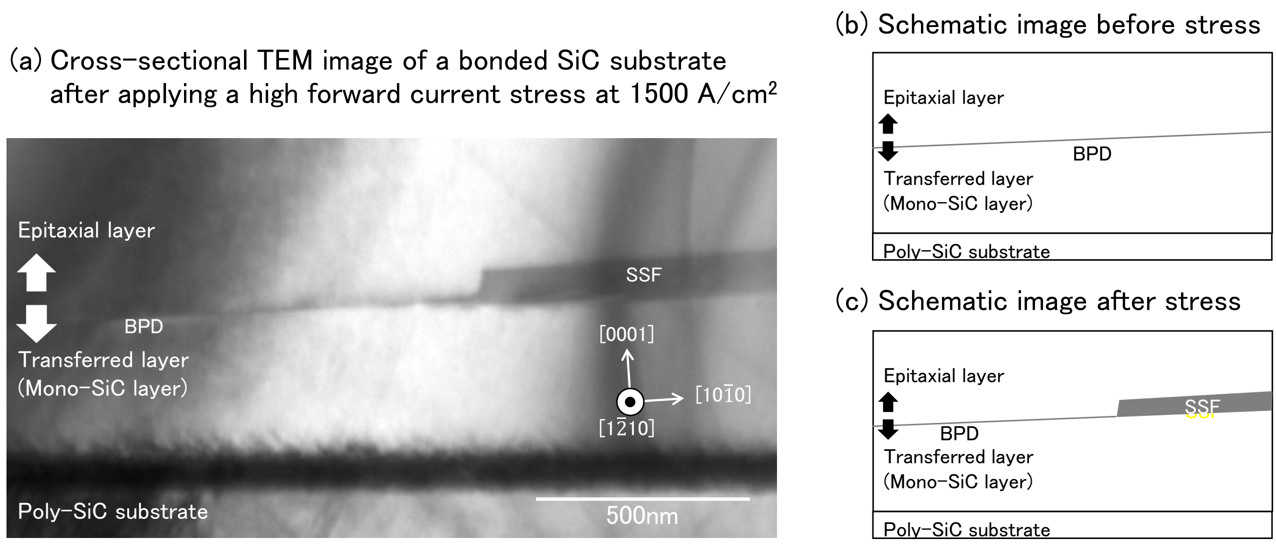

Fig. 1. (a) Cross-sectional TEM image of a PiN diode in a bonded substrate after high forward current stress at 1500 A/cm^2 and schematic diagrams (b) before forward current stress and (c) after forward current stress.

2. Evaluation of Hydrogen Implantation

TEM observations indicated that BPD expansion was suppressed in the transferred layer. To investigate the underlying reasons, we examined samples with hydrogen ions implanted into the epitaxial layer, as illustrated in Fig. 2.

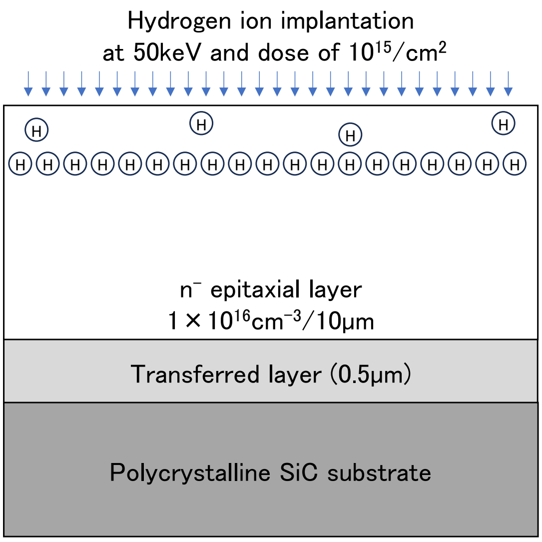

Fig. 2. Schematic diagram of the cross-sectional sample structure

Fig. 3 shows the hydrogen concentration depth profiles in the epitaxial layers. Hydrogen ions were implanted to a depth of approximately 0.5 μm from the surface of the epitaxial layer, which was adjusted to match the thickness of the transferred layer in the bonded substrate. After annealing at 1700°C, the concentration of implanted hydrogen decreased to below the detection limit of approximately 6 × 10^{16}/cm^3. The bonded substrate subjected to forward current stress was also annealed at 1700°C to reduce interface resistance, which likely removed hydrogen from the transferred layer. Despite this, SSF expansion in the transferred layer remained suppressed, indicating that factors other than hydrogen were responsible for the suppression of SSF expansion.

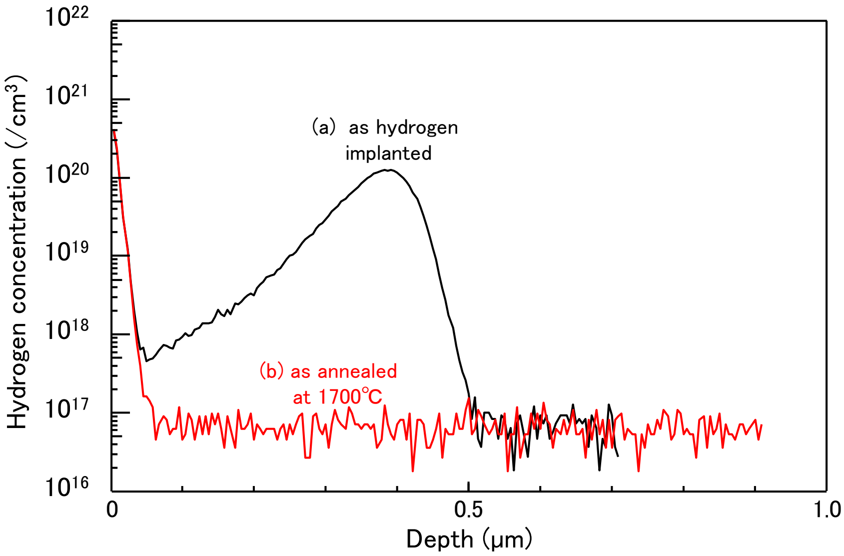

Fig. 3. Depth profiles of hydrogen concentration measured by SIMS after (a) hydrogen implantation and (b) annealing at 1700°C after hydrogen implantation

Fig. 4 shows the photoconductivity decay curves measured by μ-PCD. The carrier lifetime was defined as the time required for the photoconductivity to decay to 1/e of its initial value. Hydrogen implantation considerably reduced the carrier lifetime from 0.376 to 0.068 μs. Despite the removal of hydrogen through annealing, as indicated in Fig. 3, the carrier lifetime remained relatively short at 0.129 μs.

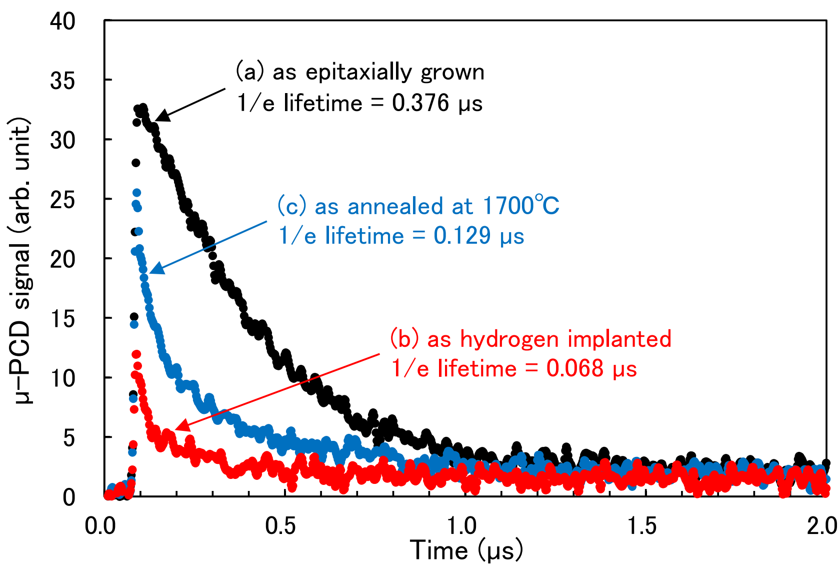

Fig. 4. Photoconductivity decay curves measured by μ-PCD after (a) epitaxial growth, (b) hydrogen implantation, and (c) annealing at 1700°C following hydrogen implantation. The laser used has a wavelength of 266 nm, with a penetration depth of approximately 1.2 μm into 4H-SiC.

It is well established that the carrier lifetime of 4H-SiC is influenced by the density of trap centers, such as the $Z_{1/2}$ center [14,15]. To investigate this, we measured the trap densities and the energy levels of various trap centers from the conduction band using DLTS. The DLTS spectra and the Arrhenius plot of $\tau_e T^2$ are presented in Figs. 5 and 6, respectively. In the plot, τ_e represents the emission time constant, T is the absolute temperature, and E_T is the energy level of the trap center. The Arrhenius plots exhibit good linearity for all samples, allowing for the calculation of trap center energy levels from the slope. Immediately after epitaxial growth, the trap center with an energy level of 0.66 eV was detected. The energy level closely matches that of the $Z_{1/2}$ center, which is associated with carbon vacancies [15, 16]. The density of the $Z_{1/2}$ center was measured at $5.3 \times 10^{12}/cm^3$. After hydrogen ion implantation, the specific trap center with an energy level of 0.97 eV increased considerably to $5.0 \times 10^{16}/cm^3$. Annealing at 1700°C caused the specific trap center to disappear, but the $Z_{1/2}$ center density increased by more than two orders of magnitude to $2.4 \times 10^{15}/cm^3$ compared to before implantation. SIMS analysis confirmed that hydrogen was removed during the annealing process at 1700°C, showing similar thermal behavior to the specific trap center, suggesting a possible association with hydrogen atoms. Further studies will be required to clarify the origin of the specific trap center. Conversely, because the $Z_{1/2}$ center is formed during annealing at 1700°C, it is expected to remain in the transferred layer of the bonded substrate even after activation annealing during the fabrication of SiC devices. The suppression effect of SSF expansion may be associated with the $Z_{1/2}$ center, formed by hydrogen implantation and the subsequent annealing.

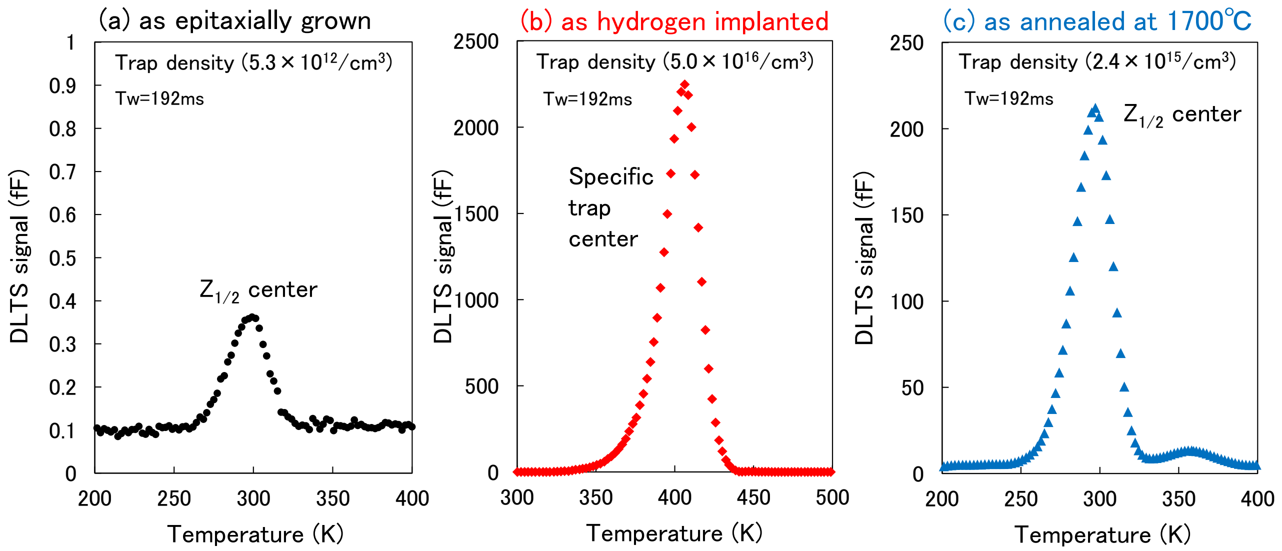

Fig. 5. Deep level transient spectroscopy (DLTS) spectra (with a period width of 192 ms) for Schottky barrier diodes after (a) epitaxial growth, (b) hydrogen implantation, and (c) annealing at 1700°C following hydrogen implantation

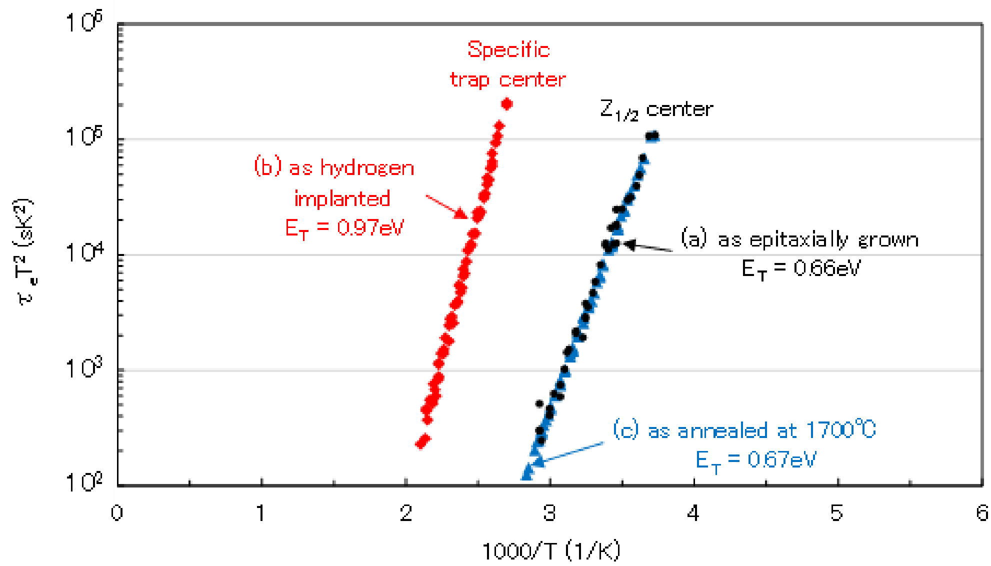

Fig. 6. Arrhenius plot of $\tau_e T^2$ for Schottky barrier diodes after (a) epitaxial growth, (b) hydrogen implantation, and (c) annealing at 1700°C following hydrogen implantation. In the plot, τ_e is the emission time constant, T is the absolute temperature, and E_T is the energy level of the trap center.

3. Discussion on Suppression of SSF Expansion in Bonded SiC Substrates

Fig. 7 shows hole movement under forward current stress in the bonded substrate. Despite the presence of BPDs in the transferred layer, which are expected to convert into TEDs near the epitaxial interface, cross-sectional TEM images in Fig. 1 confirm that BPDs did not expand into SSFs in the transferred layer even under high forward current stress. The suppression of SSF expansion is likely associated with trap centers, including the $Z_{1/2}$ center, formed by hydrogen implantation and subsequent annealing. When forward bias is applied, holes flow through the epitaxial layer and into the transferred layer. Upon reaching the transferred layer under stress, the holes are annihilated at trap centers near the epitaxial interface owing to the recombination of electron–hole pairs. Because holes do not reach the BPDs in the transferred layer, SSFs do not expand from BPDs as a result of recombination.

We have reported that no near-band-edge emission is observed in the transferred layer [3], suggesting that the presence of trap centers is likely responsible for the absence of this emission. The trap centers created by hydrogen implantation are expected to be present in the transferred layer, where they help suppress forward bias degradation in the bonded substrates by preventing SSF expansion.

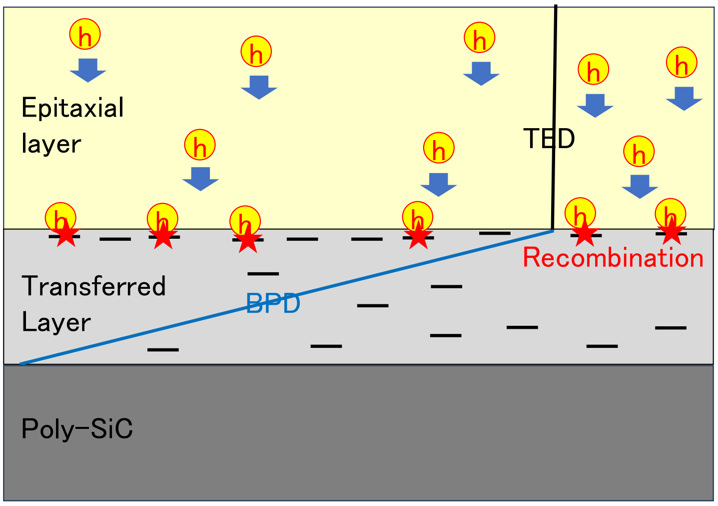

Fig. 7. Schematic diagram of hole movement under forward current stress. In the diagram, circles represent holes, arrows indicate the direction of hole movement, short lines denote trap centers, and stars represent the recombination of electrons and holes.

Summary

The generation of trap centers owing to hydrogen implantation was investigated to understand the suppression effect of forward bias degradation in 4H-SiC bonded substrates. TEM observations revealed that in the bonded substrate, the BPD did not expand into the SSF and remained unchanged in the transferred layer below the epitaxial interface, even under high forward current stress. Hydrogen implantation considerably shortened the carrier lifetime as measured by μ-PCD. Although annealing at 1700°C reduced the hydrogen concentration to below the detection limit of SIMS, the carrier lifetime remained short. DLTS measurements indicated that, following annealing at 1700°C after hydrogen implantation, the $Z_{1/2}$ center density increased by more than two orders of magnitude compared to before hydrogen implantation. It is believed that the trap centers generated by hydrogen implantation help suppress forward bias degradation in the bonded substrate by preventing the expansion of SSFs in the transferred layer.

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References

[1] T. Shimono, H. Uchida, A. Onogi, and H. Fujiwara, 7th Meeting on Advanced Power Semiconductors, IB-18, Japan (2020)

[2] N. Hatta, S. Ishikawa, K. Ozono, K. Masumoto, K. Yagi, M. Kobayashi, S. Kurihara, S. Harada, and K. Kojima, Key Eng. Mater. 948, 107 (2023)

[3] H. Uchida, M. Kobayashi, N. Hatta, S. Ishikawa, K. Ozono, K. Masumoto, S. Kurihara, S. Harada, and K. Kojima, Defect Diffus. Forum 434, 39 (2024)

[4] M. Skowronski, and S. Ha, J. Appl. Phys. 99, 011101 (2006)

[5] X. Zhang, and H. Tsuchida, J. Appl. Phys. 111, 123512 (2012)

[6] M. Abadier, H. Song, T. Sudarshan, Y. Picard, and M. Skowronski, J. Cryst. 418, 7 (2015)

[7] S. Hayashi, T. Yamashita, J. Senzaki, M. Miyasato, M. Ryo, M. Miyajima, T. Kato, Y. Yonezawa, K. Kojima, and H. Okumura, Jpn. J. Appl. Phys. 57, 04FR07 (2018)

[8] S. Hayashi, T. Yamashita, J. Senzaki, T. Kato, Y. Yonezawa, K. Kojima, and H. Okumura, Appl. Phys. Express 12, 051007 (2019)

[9] K. Konishi, R. Fujita, K. Kobayashi, A. Yoneyama, K. Ishiji, H. Okino, A. Shima, and T. Ujihara, AIP Adv. 12, 035310 (2022)

[10] A. Iijima, and T. Kimoto, J. Appl. Phys. 126, 105703 (2019)

[11] T. Tawara, T. Miyazawa, M. Ryo, M. Miyazato, T. Fujimoto, K. Takenaka, S. Matsunaga, M. Miyajima, A. Otsuki, Y. Yonezawa, T. Kato, H. Okumura, T. Kimoto, and H. Tsuchida, Mater. Sci. Forum 897, 419 (2017)

[12] S. Harada, T. Mii, H. Sakane, and M. Kato, Sci. Rep. 12, 13542 (2022)

[13] S. Harada, H. Sakane, T. Mii, and M. Kato, Appl. Phys. Express 16, 021001 (2023)

[14] K. Danno, D. Nakamura, and T. Kimoto, Appl. Phys. Lett. 90, 202109 (2007)

[15] B. Zippelius, J. Suda, and T. Kimoto, J. Appl. Phys. 111, 033515 (2012)

[16] K. Danno, and T. Kimoto, J. Appl. Phys. 100, 113728 (2006)