Ohmic contacts to \( p\text{-}6H\text{–SiC} \) using focused ion-beam surface-modification and pulsed laser epitaxial TiN deposition

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The development of low-resistance Ohmic metallizations to \( p\text{-}6H\text{–SiC} \), using a focused ion-beam (FIB)-Ga surface-modification and \textit{ex situ} pulsed laser (PLD) epitaxial TiN deposition without further annealing, is reported. The FIB-Ga surface-modification and PLD epitaxial TiN metallizations showed a minimum value of contact resistance of \( 4.4 \times 10^{-3} \ \Omega \text{cm}^2 \) at an ion dose and energy of \( 5.0 \times 10^{16} \ \text{ions/cm}^2 \) and 20 keV, respectively. Auger analysis data indicated well-defined interfaces between the metal and the semiconductor, and a significant subsurface Ga concentration. © 1998 American Institute of Physics. [S0003-6951(98)01450-8]

The development of high-quality, low-resistance Ohmic contacts that remain stable under continuous high-temperature operation is a difficult task, especially in the case of \( p\text{-}6H\text{–SiC} \). The most common approach for Ohmic contacts is believed to proceed by the formation of a heavily doped interface layer upon high-temperature annealing of an appropriate metal system\(^1\) that reduces the barrier thickness to enhance field-emission transport through the contact. It has also been reported that in alloyed contacts to GaAs, it is the substantial reduction in barrier height rather than barrier thickness that is responsible for the Ohmic character of the contacts, attributed to the formation of a highly disordered interface upon heat treatment.\(^2\) Other approaches aim at unpinning the surface Fermi level by chemical passivation,\(^3\) creating a graded lower-energy-gap interface,\(^4\) forming favorable chemical compounds (silicides),\(^5\) or implanting appropriate dopants.\(^6\) Aluminum (Al), being a \( p\text{-}type \) dopant in SiC, has been the most common system used, however, its low melting point (660 °C), oxidation, pitting, and deep spiking problems, make Al contacts inappropriate for high-temperature applications. To improve on these problems, Al/Ti\(^7,8\) and other systems\(^9,10\) based on Ti and W with some Pt and Au combinations were examined. More recently, promising approaches using sputter deposited metal borides,\(^11\) CoSi\(_2\),\(^5\) and C and Al co-implantation,\(^6\) produced values in the \( 10^{-5} \ \Omega \text{cm}^2 \) range, depending on the doping level.

In this work we report on the formation of very low contact resistance Ohmic contacts to \( p\text{-}6H\text{–SiC} \) using an approach of focused ion-beam (FIB) surface modification. Surface modification using Ga focused ion beams is aiming at lowering the surface barriers by increasing disorder, while also increasing surface doping by Ga incorporation to enhance tunneling and further improve contact resistance. In this approach, once the surface has been modified, metal deposition can be achieved either concurrently \textit{in situ} by focused ion-beam direct-write deposition of metals\(^12\) such as Pt, Mo, W, and others,\(^13\) or \textit{ex situ} by pulsed laser deposition (PLD) and other metal deposition techniques. In the case of the pulsed laser deposition reported here, TiN can be deposited either at room temperature for amorphous films or at temperatures between 600 and 800 °C for epitaxial films.\(^14,15\)

The SiC samples used in this study were \( p\text{-}type \) Al-doped \((1 \times 10^{19} \text{ cm}^{-3})\) epitaxial layers on \( n\text{-}type \) \((2 \times 10^{18} \text{ cm}^{-3})\) \( 6H\text{–SiC} \) substrates purchased from CREE Corporation. The focused ion-beam (FIB) system uses a focused beam of Ga ions, with beam energies up to 50 keV. Samples were first exposed to ion-beam doses ranging between \(8.0 \times 10^{14} \) and \(5.0 \times 10^{16} \) \text{cm}^{-2} \) and energies of 20, 30, and 50 keV. TiN was then deposited over the whole sample by pulsed laser deposition. Both amorphous (room-temperature) and epitaxial (600 °C) TiN films of approximately 1000 Å were deposited in this work for comparison. The transmission line model (TLM) for contact resistance measurement\(^16\) was used on all contacts. The measurements provide the specific contact resistance value \( r_C \) for the contacts, which we refer to as the contact resistance, for simplicity. The TLM patterns were defined by standard photolithography on both the surface-modified and unmodified areas in order to assess the effects of the surface-modification process. The surface-modified areas were rectangular areas defined by the focused ion-beam and were large enough to contain several TLM patterns without strict alignment requirements. Once the photolithography patterns were developed, the unprotected TiN metal was removed by Ar ion milling. Optimized conditions for metal removal were an Ar ion energy of 0.5 keV with a beam current of 15 mA for a removal rate of 50 Å/min.

The TiN contacts deposited at room temperature were found to be amorphous layers. When the substrate temperature during PLD growth is elevated to 550 °C, x-ray \( θ\text{–}2θ \) diffraction analysis showed that the TiN films begin to grow.

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epitaxially. The x-ray analysis of a 200 nm thick TiN film deposited by PLD on 6H–SiC(0001) at 650 °C, is shown in Fig. 1. The analysis clearly shows the $\{111\}$ family of planes of TiN aligned parallel to the $\{0002\}$ planes of the SiC substrate. Rocking curve data of the TiN peak showed a full width at half maximum (FWHM) of 0.35°, indicating a good alignment of the TiN $\{111\}$ planes parallel to the SiC substrate $\{0001\}$ planes.

The contact resistance $r_C$ measurements of the amorphous TiN contacts on surface-modified and unmodified $p$-6H–SiC produced contact resistance values of $r_C = 3.2 \times 10^{-4}$ Ω cm² and $r_C = 2.8 \times 10^{-3}$ Ω cm², respectively, at an energy $E = 30$ keV and dose $D = 1.5 \times 10^{15}$ ions/cm². This is a reduction of nearly one order of magnitude in contact resistance for the surface-modified contacts, and it establishes the importance of the step in the contact formation process. For a higher ion energy $E = 50$ keV and the same dose $D = 1.5 \times 10^{15}$ ions/cm², the contact resistance value is measured to be $r_C = 6.0 \times 10^{-4}$ Ω cm², showing an increase of approximately a factor of 2 as compared with the 30 keV value, indicating that the lower end of focused ion energies produces lower contact resistance values.

Figure 2 shows the TLM measurements of the TiN contacts deposited epitaxially by PLD at 600 °C on surface-modified and unmodified areas of $p$-6H–SiC. In this case, a minimum contact resistance value of $r_C = 4.4 \times 10^{-5}$ Ω cm² is obtained at a focused ion-beam dose and energy of $D = 5.0 \times 10^{16}$ ions/cm² and $E = 20$ keV, respectively. This contact resistance value is comparable to or lower than the values reported for $p$-6H–SiC. The contact resistance value for the unmodified area of the epitaxial PLD contacts is $r_C = 8.5 \times 10^{-4}$ Ω cm², clearly over one order of magnitude higher than the value for the modified contact, but lower than the corresponding value of the unmodified amorphous PLD contacts, demonstrating the additional benefits from the PLD epitaxial deposition process. A dramatic decrease in contact resistance values is observed with increasing ion doses, reaching a plateau of minimum contact resistance at ion doses beyond $8.0 \times 10^{15}$ ions/cm², as shown in Fig. 3. Furthermore, the increase in contact resistance in the higher ion energy (30 keV, solid line) as compared with that of the lower energy (20 keV, dotted line) surface modification is evident here also, as it was observed in the amorphous contacts above. The Auger depth profile of the surface-modified sample is shown in Fig. 4. The depth profile shows a well-defined interface with significant concentrations of Ti, N, TiN, Si, and C, and an interface peak of Ga. No chemical reactions at the interface are evident, and the oxygen concentration in the film was observed only in this sample. Ga is detected within the first 15 nm of the SiC interface, and it is estimated to be in the range of a few atomic percent (~4%).

The results here show that focused ion-beam (Ga) surface modification reduces the contact resistance in $p$-type SiC substantially. The factors that affect the process of Ohmic contact formation using FIB surface modification are related to the energy and dose of the focused ion beam, as well as the metal deposition process. Lower beam energy (20 keV) would be beneficial for reducing the contact resistance, as shown in Fig. 3.

**Fig. 1.** X-ray diffraction scans of a 200 nm thick TiN deposited by PLD on 6H–SiC (0001) at 650 °C.

**Fig. 2.** TLM contact resistance measurements of epitaxial PLD TiN contacts on surface-modified and unmodified $p$-6H–SiC, for two different energies and doses. For clarity, only two doses are shown.

**Fig. 3.** Contact resistance values of epitaxial PLD TiN with ion-beam dose and energy. The plateau of minimum resistance is reached at a dose of $8.0 \times 10^{16}$ ions/cm². The unmodified surface has a contact resistance value $r_C = 8.5 \times 10^{-4}$ Ω cm².
keV) is observed to produce lower contact resistance values than the higher-energy (30 or 50 keV) regime, indicating that Ga penetration deeper from the surface is not advantageous for the contacts. The ion dose is observed to have a more profound effect on the contact resistance values of the contacts. Here, a large decrease of contact resistance values is observed with increasing dose up to a threshold dose of 8.0 \times 10^{16} \text{ ions/cm}^2, beyond which a plateau of minimum contact resistance is reached (Fig. 3), indicating that a minimum dose is necessary before disorder becomes important to substantially reduce contact resistance. The incorporation of such high levels of Ga atoms will increase the disorder at the interface substantially and create a heavily intermixed Si-GaC interface layer with a reduced barrier height,\(^2,17\) to explain the reduction in contact resistance and formation of such \(p\)-type Ohmic contacts. Other factors that may contribute to the reduction of the contact resistance, such as the reduction of the thickness of the barrier due to increased interface doping by activating the incorporated Ga atoms, need to be considered also. Since Ga is also a potential \(p\)-type dopant in SiC,\(^18\) the possibility exists for some of the Ga atoms to get activated if incorporated in the appropriate lattice sites in SiC. Although the TiN epitaxial deposition (600 °C) and surface-modification step showed a substantial reduction in contact resistance, a decrease in contact resistance was also evident between the unmodified (no Ga) amorphous (2.8 \times 10^{-3} \text{ \Omega cm}^2) and unmodified epitaxial (8.5 \times 10^{-4} \text{ \Omega cm}^2) contacts, which, since no Ga is present at the interface, suggests an improved metal-to-semiconductor interface due to epitaxial growth rather than any activation of Ga atoms. Activation of implanted \(p\)-type dopants like Al in SiC has been reported\(^19\) to require both elevated temperatures (700 °C) during implantation and high-temperature (1500 °C) postimplantation annealing. Ga, like Al, would require comparable temperature heat-treatment levels to become activated in SiC, which are not available in our process. Therefore, it is considered unlikely that any Ga activation takes place in these contacts due to the 600 °C temperature required for the deposition of the epitaxial metal. Furthermore, the effects of the interaction of the ion beam with the surface of the semiconductor need to be studied further.\(^20\)

In conclusion, Ohmic contact formation to \(p\)-6H–SiC using an approach of focused ion-beam surface modification, produced a contact resistance value of 4.4 \times 10^{-5} \text{ \Omega cm}^2 for epitaxial PLD TiN. The FIB surface-modification process resulted in over one order of magnitude improvement in the contact resistance values. The amorphous TiN contacts showed the same behavior as a function of ion-beam dose and energy with the epitaxial ones, but with significantly increased values of contact resistance, indicating the advantages of the PLD epitaxial process. A minimum contact resistance plateau is reached with FIB surface-modification ion doses equal to or larger than 8.0 \times 10^{15} \text{ ions/cm}^2, and at lower ion energies. Auger and SIMS analysis data indicate an intermixed Si(Ga)C interface layer, which is believed to be responsible for the reduction in contact resistance.

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