Pt and W Ohmic Contacts to p-6H-SiC by Focused Ion Beam Direct-Write Deposition

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Low resistance Pt and W ohmic metallizations to p-type 6H-SiC, using focused ion beam (FIB) surface-modification and in-situ direct-write metal deposition without annealing, are reported. FIB(Ga) surface-modification and in-situ deposition of Pt, and W showed minimum contact resistance values of 2.8×10^{-4} ohm-cm^2 to 2.5×10^{-4} ohm-cm^2, respectively. A comparison with ex-situ pulse laser deposited Pt on surface-modified areas showed comparable contact resistance values and similar behavior. Auger and secondary ion mass spectroscopy analysis showed a significant (~4% a.c.) incorporation of Ga within a 15 nm distance from the SiC surface with surface-modification. Atomic force microscopy studies showed that surface-modification process smooths out the SiC surface significantly.

Key words: Focused ion beam (FIB), ohmic, p-6H-SiC, surface modification

INTRODUCTION

The development of low resistance, high quality ohmic metallization schemes to n and p-type SiC has attracted significant attention, since the performance of devices[1] critically depends on the performance of the ohmic contacts especially under high power/high temperature operation. A common approach for ohmic contact formation proceeds by high temperature annealing of an appropriate metal system,[2] which is thought to create a heavily doped interface layer that reduces barrier thickness enhancing field emission transport through the contact. It has also been reported that in alloyed AuGe contacts to GaAs, it is the substantial reduction in barrier height (rather than thickness) attributed to the formation of a highly disordered interface, that is responsible for the ohmic character of the contacts.[3] Aluminum (Al), being also a dopant in p-type SiC, has been the most common system used for p-type ohmic contacts, but its low melting point (660°C), oxidation, pitting and deep spiking problems make this system inappropriate for high temperature applications, and Al/Ti[4,5] is used to improve on these problems. Other promising approaches aim at unpinning the surface Fermi level to reduce the barrier height,[6] forming favorable chemical compounds (silicides),[7] using refractory metal borides,[8] or increasing doping by implantation of appropriate dopants and codopants.[9]

In this work, we propose an alternative new approach to ohmic contact formation using focused ion beam (FIB) surface-modification and direct-write metal deposition, without annealing. Focused ion beam systems are capable of generating high intensity ion beams,[10] that can modify the surface of the semiconductor to such an extent that subsequent metal deposition may result in the formation of an ohmic contact. This approach of surface-modification using focused ion beams is aimed at lowering the surface barriers by increasing disorder due to the restructuring of the surface and the incorporation of the ions in the crystal lattice. Ga, being the most common ion used in FIB systems, is also a potential dopant[11] in p-type SiC, which provides the additional possibility of improving ohmic contacts by increased surface doping. Metal deposition can be accomplished either in-situ, by introducing an appropriate precursor to the focused beam for direct-write metal deposition,[12] or ex-situ by any other deposition technique such as pulsed laser deposition (PLD).[13,14] Since FIB is

(Received July 20, 1998; accepted October 9, 1998)

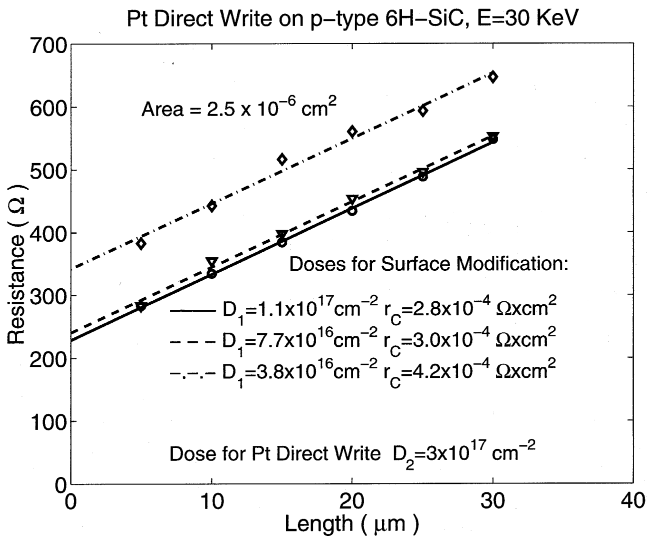

Fig. 1. TLM pattern measurements of the two-step Pt direct-write deposition in-situ the FIB system. Ga ion beam doses for the surface-modification step and corresponding contact resistance values of each sample are indicated in the inset along with the dose for the direct write deposition. From the slope of the lines the sheet resistance R_c = 26 Ω/□ is extracted. Only three lines are shown for clarity.

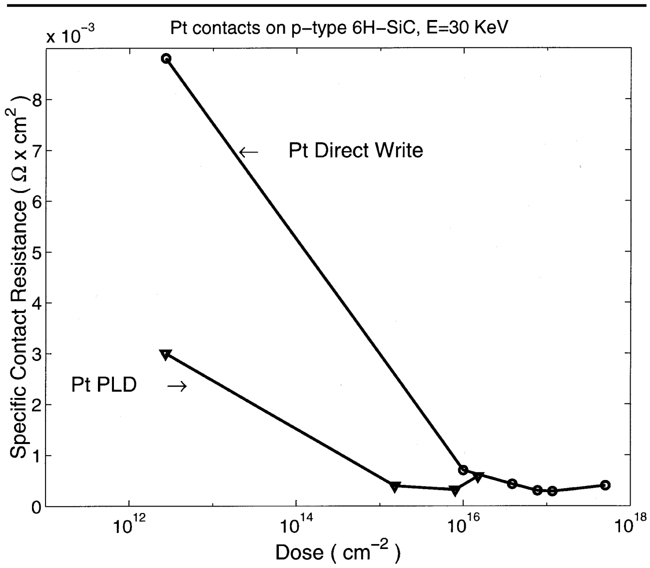

Fig. 2. Summary of the contact resistance values with Ga ion beam dose for Pt direct-write deposited in-situ the FIB system and Pt deposited ex-situ by PLD. Ion beam energy is 30 keV for the direct-write Pt and 20 keV for the PLD Pt deposition.

capable of modifying the surface as well as depositing metals, a complete process that excludes the possibility of interface contamination can be achieved.

In the following, the formation of low contact resistance Pt and W ohmic contacts to p-type 6H-SiC using focused ion beam surface modification and in-situ direct-write metal deposition without annealing is presented, and the process of surface-modification and the parameters critical to contact formation, are discussed.

EXPERIMENTAL DETAILS

The SiC samples used in this study were p-type Al-doped (1×10^{19} cm^{-3}) epitaxial layers on n-type (2×10^{18} cm^{-3}) 6H-SiC (0001) substrates purchased from CREE Corporation. The FIB system uses a beam of Ga ions, with beam energies of 20 and 30 keV. The direct-write deposition of Pt and W is accomplished by introducing dimethyl-methyl-cyclopentadienyl-Pt and W $(CO)_6$, respectively, in the stream of the Ga beam,[10] breaking up the compound to effect the direct-write deposition of each metal. Depending on exposure, ion beam dose, and energy, deposited metal thicknesses of a few monolayers to microns, can be achieved.

Samples were first exposed to the Ga beam for the surface-modification step and then to the direct-write metal deposition step. This two-step process allows the flexibility to select ion doses for the surface modification step independently from the direct-write metal deposition step for better control over the process. The transmission line model (TLM) for contact resistance measurements was used on all contact systems. The measurements provide the specific contact resistance values, r_c, for the contacts,[15] which are referred to as the contact resistance values for simplicity. Since this is a direct-write process, the TLM pattern can be defined either by exposing a larger area to the surface-modification step and then depositing the series of individual contacts on this area, or by depositing each contact individually leaving the rest of the surface between contacts unaltered. Ion beam doses for surface-modification ranged between 1.0×10^{16} cm^{-2} and 8.0×10^{17} cm^{-2} at an ion beam energy of 30 keV, while the doses for the subsequent Pt and W direct-write metal deposition step were 3.0×10^{17} cm^{-2} and 5.2×10^{16} cm^{-2}, respectively, at the same ion beam energy. For comparison, Pt was also deposited ex-situ by PLD using a KrF excimer laser for ablation[13] of a Pt target. The ex-situ metal was deposited epitaxially[16] at 600°C, over both surface-modified and unmodified areas concurrently. The ion beam doses for this sample ranged between 1.5×10^{15} cm^{-2} and 1.5×10^{16} cm^{-2} at an ion beam energy of 20 keV, and the TLM contact pattern was defined by standard photolithography and Ar ion etching.

Auger depth profiling (AES) and secondary ion mass spectroscopy (SIMS) are used to examine the metal/semiconductor interface and correlate with the observed electrical properties. Atomic force microscopy (AFM) is employed to examine the surface morphology before and after surface-modification.

RESULTS AND DISCUSSION

The TLM contact resistance, r_c, measurements of the direct-write Pt contacts on surface-modified and unmodified p-6H-SiC are shown in Fig. 1. For clarity, only three different doses are included in the figure. A minimum contact resistance value of $r_c = 2.8 \times 10^{-4}$ ohm cm^2 for the surface-modified areas is obtained at a dose $D = 1.1 \times 10^{17}$ ions/cm^2 and energy E = 30 keV. The unmodified areas produced a contact resistance value $r_c = 8.8 \times 10^{-3}$ ohm cm^2, which is over one order of magnitude higher than that of the surface-modified areas. The significant reduction in contact resistance from the unmodified to the surface-modified areas, establishes the importance of the step in the contact formation process.

The contact resistance measurements of the Pt contacts deposited epitaxially by PLD at 600°C on surface-modified and unmodified areas of p 6H-SiC, produced a minimum contact resistance value of r_c = 3.0×10^{-4} ohm cm^2 at a focused ion beam dose and energy of D = 8.0×10^{15} ions/cm^2 and E = 20 keV, respectively. This contact resistance value is comparable to the one obtained from the direct-write Pt contacts, but at lower ion doses. The contact resistance value for the unmodified area of the epitaxial PLD Pt contacts is $r_c = 3.2 \times 10^{-3}$ ohm cm^2, which is significantly higher than the value for the surface-modified contacts, but lower than the corresponding value of the unmodified amorphous direct-write Pt contacts. In our work, the epitaxially deposited metals are observed to produce a lower value of contact resistance than corresponding amorphous metallizations, suggesting that the growth temperature of 600°C required for the epitaxial PLD metal deposition and the epitaxial character of the metal may result in a more intimate interface between the metal and the semiconductor.

Figure 2 summarizes the results of the contact resistance for the direct-write and the PLD deposited Pt contacts with ion dose. As can be seen, the direct-write Pt contacts produce contact resistance values ranging from a maximum value of $r_c = 7.4 \times 10^{-4}$ ohm cm^2 at the lower dose (D = 1.0×10^{16} ions/cm^2) to a minimum value of $r_c = 2.8 \times 10^{-4}$ ohm cm^2 at the higher dose (D = 1.1×10^{17} ions/cm^2), increasing again to a value of $r_c = 4.1 \times 10^{-4}$ ohm cm^2, at the highest dose (D = 1.0×10^{18} ions/cm^2), indicating an optimum dose around 1×10^{17} ions/cm^2 for minimum contact resistance. The PLD epitaxial Pt contacts showed comparable contact resistance values but for lower doses. Increasing the dose in these contacts may improve contact resistance further.

The direct-write deposition of W on surface-modified and unmodified areas, also produced contact resistance values comparable to the Pt direct-write contacts with a minimum value $r_c = 2.5 \times 10^{-4}$ ohm cm^2, as shown in Fig. 3, where the contact resistance results are summarized with ion beam doses and energy. As in the Pt contacts, the unmodified W contacts produced a contact resistance value $r_c = 8.7 \times 10^{-3}$ ohm cm^2, over one order of magnitude higher than the modified contacts.

The process of surface-modification and direct-write is examined by AES and SIMS to define the interface and Ga incorporation. The Auger depth profile of the surface-modified (two-step) sample and that of an unmodified sample (direct-write step only) is shown in Fig. 4a and 4b, respectively. The depth profile shows a well-defined interface where no chemical reactions are evident, and significant concentrations of Si, C, Pt, and Ga are present. The direct-write Pt film also has significant concentrations of C, and lower concentrations of Ga (incorporated as expected by the FIB process) and Si incorporated in the metal by outdiffusion from the substrate. The C concentration observed in the Pt direct-write deposited films is originating from the dimethyl-methyl-cyclopentadienyl-Pt precursor used in the FIB process for the metal deposition. This C concentration is observed to merge at the interface with the C of the SiC substrate (small depression where the two distributions merge),

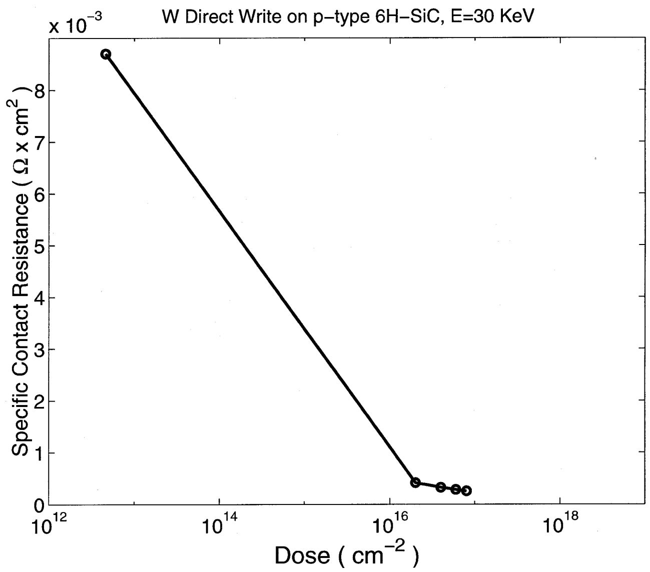

Fig. 3. Summary of the TLM measurement contact resistance values with Ga ion beam dose for W direct-write contacts deposited in-situ the FIB system. Here the minimum contact resistance value of r_c = 2.5×10^{-4} ohm cm^2, is obtained for ion doses (6.0–8.0 $\times 10^{17}$ cm^{-2}) higher than those for the direct-write Pt.

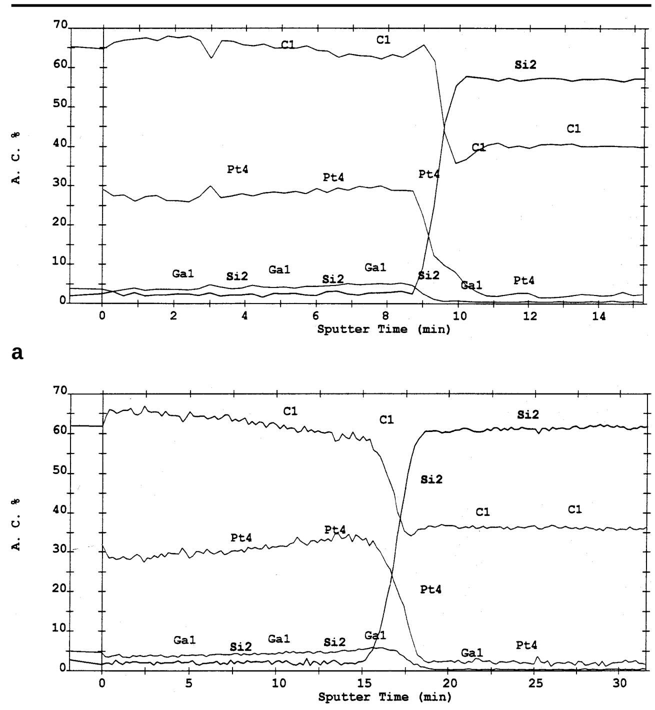

Fig. 4. (a). Auger depth profile of the Pt direct-write contacts without the surface-modification step. Here the Ga incorporation at the interface is observed to be limited. (b). Auger depth profile of the Pt direct-write contacts with surface-modification. The Ga incorporation here is observed to be substantial within a 15 nm interface SiC layer.

while the Ga concentration incorporated by the surface-modification step is observed to merge with that of the direct-write Pt deposition (Fig. 4a). As compared with the unmodified contact where only the direct-write step is applied (Fig. 4a), the Ga concentration is substantially larger and significantly deeper in the interface of SiC when the surface-modification is applied (Fig. 4b). SIMS analysis (Fig. 5) of the interface of a sample surface-modified but ex-situ deposited with a film of TiN by PLD, shows clearly the Ga concentration peak due to the surface-modification at the SiC interface without the influence of the Ga concentration in the direct-write deposition of the metal film, supporting the Auger analysis data. This Ga concentration is approximately at 4% a.c., within a 15 nm depth of the SiC surface and appears to be critical to the process. The incorporation of such level of Ga concentration will increase the disorder at the interface substantially and create an intermixed Si(Ga,Pt)C intermediate layer, resulting in a lower barrier[3] and the observed reduction in contact resistance.

Another factor, however, that may contribute to the reduction of the contact resistance by thinning the barrier, is the possibility of high interface doping by activating Ga as an acceptor in the SiC lattice. Henry et al.[11] have examined Ga as a potential p-type dopant in SiC by photoluminescence and reported an acceptor state at 29–37 meV from the valence band, suggesting that Ga can become a p-type dopant in SiC, if activated. Since activation of implanted dopants like Al in 6H-SiC has been reported[17] to require high temperature (1600°C) annealing, one would expect Ga, having a significantly larger mass number than Al, to require at least as high a temperature annealing as Al for activation. Therefore, the 600°C required for the epitaxial deposition of the metal, is insufficient for any activation to occur. In addition, a comparison (Fig. 2) of the contact resistance values between the direct-write unmodified Pt contact (8.8×10^{-3} ohm cm^2) and the unmodified (no Ga) PLD epitaxial Pt contact (3.2×10^{-3} ohm cm), still shows a decrease in contact resistance for the epitaxial contact, which, since no Ga exists at the interface, leads us to believe that although theoretically possible, Ga activation is unlikely.

The effect of the surface-modification on the surface morphology of the samples, was examined by AFM. A series of areas were surface-modified at doses varying between 1.0×10^{16} cm^{-2} and 8.0×10^{16} cm^{-2}, and the AFM images were obtained, as well as line traces for roughness measurements. Figures 6a–6d, show the AFM images and line scans of the SiC surface prior to modification (a), (b), and after modification (c), (b) with a high dose. As can be seen in Fig. 6a, the unmodified SiC surface presents an undulating surface morphology typical of our samples, indicating roughness feature sizes of the order of 4 to 7 nm as shown in the line scan of Fig. 6b. When the surface-modification process is applied, the undulating morphology of the surface rapidly disappears with increasing dose, Fig. 6c, to produce a smooth surface morphology having one order of magnitude lower roughness feature size (~0.7 nm) than the unmodified surface, as observed in the line scan in Fig. 6d. The observed smooth surface morphology can be attributed to the restructuring of the surface, although some material removal expected at the higher ion beam doses may also contribute to the smooth morphology of the modified surface.

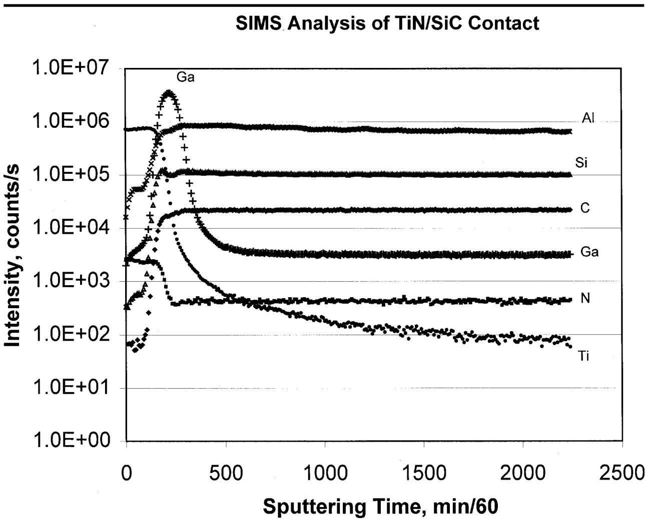

Fig. 5. SIMS analysis of surface-modified SiC with ex-situ TiN pulsed laser deposited contacts. The Ga concentration peak due to the surface-modification step is clearly evident here, along with the Al doping concentration of the SiC epitaxial layer that cannot be detected in the Auger data. The Al concentration here appears to be high, but it is much lower than that of C due to much higher Al sensitivity, and that of Si due to the use of a low (4.6%) abundance isotope for Si (29Si).

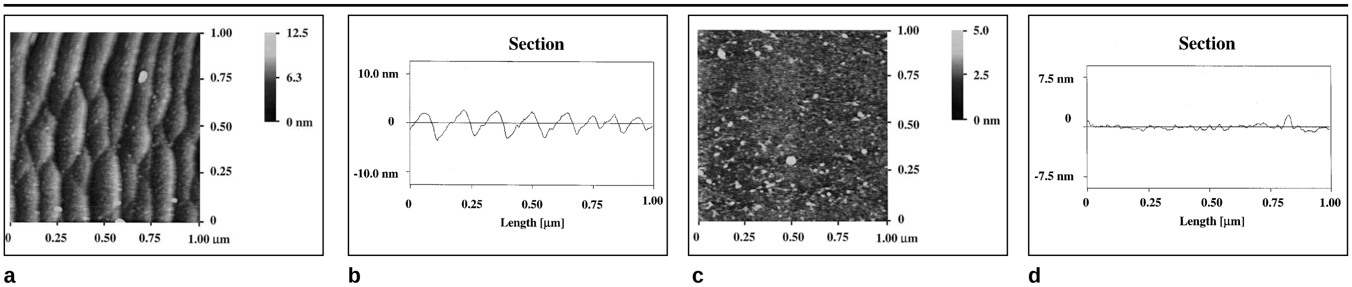

Fig. 6. (a). Atomic force microscopy image and line trace of the SiC surface prior to surface-modification. Undulating surface morphology is evident in this image. (b) Line scan of the surface showing roughness features of ~4 to 7 nm, and a period of 100 to 150 run. (c) Atomic force microscopy image of the SiC surface after high dose surface-modification. Surface morphology appears to have been smoothed out. (d) Line scan shows roughness features reduced by one order of magnitude to ~0.7 nm, indicating a substantial restructuring of the surface.

SUMMARY

Ohmic contact formation in a two-step process of focused ion beam surface-modification and in-situ direct-write metal deposition of Pt and W, is presented. Surface-modification is observed to reduce specific contact resistance values by over one order of magnitude for both metal systems. Auger and SIMS analysis showed that the surface-modification step incorporates a substantial Ga concentration within a 15 nm of the SiC surface, resulting in a highly disordered interfacial layer and the substantial reduction of the specific contact resistance of both metal systems. Contact resistance values obtainecd in this work, are comparable with values from more conventional approaches that include high temperature annealing steps. The improvement in surface morphology after the application of the surface-modification step seen in the AFM images, may be attributed to the restructuring of the surface and may have important implications in the development of devices with planar contacts.

ACKNOWLEDGMENTS

The authors would like to thank Dr. John Melngailis for helpful discussions and Dr. Mel Gomez for his help with the AFM data. This research was funded by the U.S. Army Research Laboratory under Cooperative Agreement No. DAAL01-95-2-3530.

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