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Effect of n^+-GaN subcontact layer on 4H–SiC high-power photoconductive switch

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High-power photoconductive semiconductor switching devices were fabricated on 4H–SiC. In order to prevent current crowding, reduce the contact resistance, and avoid contact degradation, a highly *n*-doped GaN subcontact layer was inserted between the contact metal and the high resistivity SiC bulk. This method led to a two orders of magnitude reduction in the on-state resistance and, similarly, the photocurrent efficiency was increased by two orders of magnitude with the GaN subcontact layer following the initial high current operation. Both dry etching and wet etching were used to remove the GaN subcontact layer in the channel area. Wet etching was found to be more suitable than dry etching. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1951056]

Since first described by Auston[1] in 1975, photoconductive semiconductor switches (PCSSs) have been investigated intensively for many applications owing to their unique advantages over conventional gas and mechanical switches. These advantages include high breakdown field, high speed, long lifetime, and negligible jitter. The advantages of PCSSs make them a perfect choice for many important applications where high switching accuracy and high-power capability are required, some examples of which are microwave and millimeter wave generation, impulse radar, and pulsed power systems.[2] Most PCSSs reported to date have been fabricated in Si and GaAs. However, Si and GaAs have critical intrinsic limitations in operations at high fields, high temperatures, and high radiation levels.[3,4] In recent years, there has been a great deal of interest and extensive effort in the development of SiC power switches owing to excellent properties of SiC in this respect. SiC is resistant to chemical attack and radiation, and stable at high temperatures.[5] Compared to GaAs and Si, SiC has a higher saturation electron drift velocity, thermal conductivity, and breakdown field.[6,7] For the same breakdown voltage, the on-state resistance of a SiC device is expected to be lower by two orders of magnitude than that for Si because smaller layer thicknesses and or higher doping levels can be used.[8] Therefore, SiC-based PCSSs are expected to have much better performance and wider applications than those of GaAs and Si.[9–11] Initial results for PCSSs fabricated on 6H–SiC and 4H–SiC have been reported.[9,12] A small on-state resistance is a critical parameter for a switching device for reduced power dissipation during the on state.[13] The on-state resistance of a switching device not only depends on the properties of the semiconductor material used, but also on the contact properties. The contact problems are exacerbated by the need for high-temperature high-power operation expected of SiC devices.[5] In this letter, we report on the fabrication and characteristic of PCSSs on 4H–SiC utilizing a n^+-GaN subcontact current spreading layer. The highly doped GaN epitaxial subcontact layer was grown by organometallic vapor phase epitaxy (OMVPE) on SiC to improve the ohmic contact and mitigate the current filamentation.

The devices were fabricated in a lateral configuration with circular geometry with channel lengths of 0.5, 0.75, 1.25, and 1.75 mm. All of the devices have an inner contact diameter of 1.5 mm. This circular geometry used is well suited for minimizing the spurious edge field effects by preventing larger fields from forming at the edges, thus helping to increase the breakdown voltage.[14] The different channel lengths are designed to test the dependence of the breakdown voltage on the channel length. The dimensions were chosen by considering the dielectric breakdown field strength of air which is about 30 kV/cm. Devices were fabricated on vanadium-doped 4H semi-insulating (SI) and 4H high-purity SI (HP-SI) SiC substrates with the same fabrication process.

In order to get a smooth surface at the atomic scale, a high-temperature H_2 etching process by inductive heating was used to remove the surface damaged present in the as-received material.[12,15] A 100 nm n^+-GaN epilayer with a high doping level of 3×10^{19} was grown by OMVPE on both 4H SI and 4H HP-SI SiC substrates. The GaN layer was removed in the channel area by both dry and wet etching, for comparison. The wet etching process was performed in a 80% KOH solution at 130 °C for 3 min. The etched surface had a surface roughness comparable to the control surface, as characterized by an AFM. The dry etching step was performed with BCl_3 reactive ion etching. The process parameters are as follows: 300 W rf power, 15 sccm BCl_3, 60 mTorr chamber pressure, etching time of 5 min. Ni/Ti/Au (500 Å/300 Å/750 Å) and Ti/Al/Ti/Au (300/2000/300/300 Å) metal stacks were deposited, for ohmic contacts

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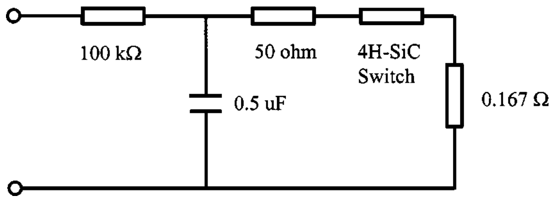

FIG. 1. The diagram of the circuit used for testing 4H–SiC switching devices.

to SiC surface and GaN coated surface, respectively, by e-beam evaporation (for Ni and Ti) and thermal evaporation (for Au, Al). The ohmic contacts were formed with rapid thermal annealing (RTA) in a nitrogen ambient at 950 °C for 1.5 min, and 900 °C for 60 s, respectively.

The photoconductivity of the switching devices was measured under high dc voltage using a *Q*-switched frequency tripled YAG laser at 355 nm with a pulse width of 10 ns. The test circuit is shown in Fig. 1. A charged 0.5 μF capacitor in parallel with the device was used to provide a source of current during the photoconductive pulse. A 0.167 ohm noninductive current sense resistor in series with the switch was used to measure the photocurrent through the device.

The dark resistance of devices with and without GaN was measured, the latter turning out to be higher. For a switchin 4H HP-SI SiC device with 1.75 mm channel, the dark resistance without GaN (No. G7) is 5×10^{10} ohm. With a GaN contact layer, the device (No. G8) dark resistance decreased to 3×10^{9} ohm, as a result of reduced contact resistance and thereby the series resistance culminating in the expected increase in the measured dark current. The GaN layer should not affect the hold-off voltage, which is mainly related to the semiconductor channel and channel surface conditions.

Figure 2 shows the dark resistance for devices with different channel lengths. For devices without a GaN subcontact layer (No. G6), the dark resistance has no clear relationship to the channel length. This reflects the difficulty in achieving ohmic contacts on low-doped or SI semiconductors, and current conduction paths are subject to the local properties of the SiC bulk. For devices with a GaN subcontact layer (No. G8), not only an obvious decrease of dark resistance was observed, but also a relationship can now be seen between the device dark resistance and channel length except for an outlier at the smallest channel length.

Photoconductive measurement of the fabricated switching devices showed excellent performance. Photocurrent levels up to 200 A and breakdown voltages up to 2900 V have been observed in the devices fabricated on SiC. However, the contact at the cathode in these devices gets damaged at high photocurrent levels, which prevented testing at higher voltages. After the contact damage, the photocurrent for the same optical excitation decreased dramatically. The contact at the anode collecting the electrons was not damaged. After damage, the contact at the cathode metal surface turned black, which is most likely due to titanium diffusion through gold followed by oxidation and formation of TiO_x.[16]

Contact degradation limits device performance well below that which can be expected from the intrinsic properties of the semiconductor in use. The basis for the degradation mechanism in laterally configured contacts is as follows: The holes with lower mobility and diffusion constant are col-

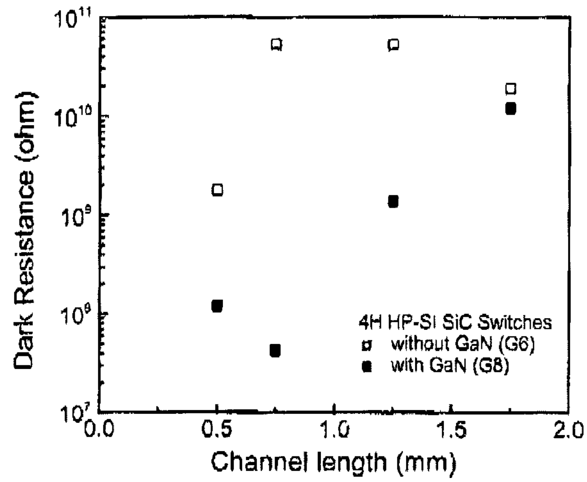

FIG. 2. Dark resistance vs the channel length for devices (□) without and (■) with a 100 nm high conductive *n*-GaN subcontact layer. The data for the device without the GaN layer are scattered, however the data for the case with the GaN layer, with the exception of the shortest channel length, exhibit the expected dependence on channel length.

lected by the cathode (negatively biased electrode) and electrons are collected by the anode (positively biased electrode). Due to the smaller mobility/diffusion constant for holes as compared to electrons, the current under the cathode tends to be focused at the contact/semiconductor edge. In other words, the current is not uniformly distributed through the entire contact area but flows only in a small part of contact area.[17] Quantitatively, the electron mobility in SiC is 600–1000 $cm^2/V\,s$, while the hole mobility is only 40 $cm^2/V\,s$.[5] Therefore, the joule heating at the cathode is much more prevalent than that at the anode, which causes the contact damage at the cathode. This is in spite of the fact that the current density is higher at inner contact (anode, for the bias conditions chosen) due to the smaller size compared to the outer contact size (cathode).

In contrast, our SiC switching devices with GaN subcontact layers exhibited higher photoefficiency than those without GaN. Moreover, the contact degradation was not observed in devices with a GaN subcontact layer. This lack of degradation can be attributed to the heavily doped GaN layer under the contact being able to collect holes more efficiently over a relatively larger area. With the n^+ -GaN subcontact layer, the ohmic contact improves, in addition to being ohmic, as compared to the contacts directly on the very high resitivity SiC, and thus the reduced contact resistance alleviates the heating.

The photoresponse for devices with and without a GaN subcontact layer is shown in Fig. 3. Figure 3(a) shows the photocurrent of a device with GaN subcontact layer at different biases, excited at a relatively low laser energy of 0.06 μJ. The peak photocurrent increases from 1.02 to 7.84 A with corresponding bias increasing from 100 V to 900 V. The photocurrent efficiency is 1.45×10^{-1} A/μJ V. From the photoresponse, it can be calculated that the on-state resistance is 1.15×10^{2} ohm. So the off/on resistance ratio is 2.6×10^{7}. Figure 3(b) shows the photoresponse for a device without a GaN subcontact layer after contact damage. The photocurrent is 0.13 A to 0.23 A with the bias from 1700 V to 2500 V. The corresponding efficiency is only 3.68 $\times10^{-3}$ A/μJ V, which is two orders of magnitude lower than that of the device with GaN subcontact layer. The cor-

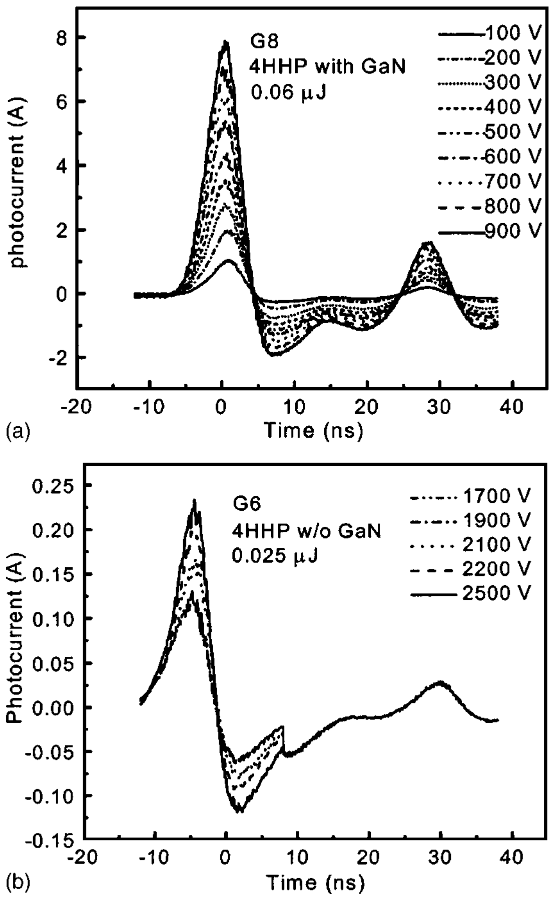

FIG. 3. Photocurrent of the 4H HP SI SiC switching device (a) with GaN subcontact layer and (b) without GaN subcontact layer with contact damaged.

responding on-state resistance is 1.09×10^4 ohm, which is two orders of magnitude higher than that with GaN.

The characteristics shown Fig. 3(b) associated with sample No. G8 have been obtained when the GaN layer was removed using the damage free KOH wet etching. The results indicate that this process did not bring about any degradation. However, the dry etching process could adversely affect the device by damaging the SiC surface in the channel area. Figure 4 shows the photocurrent of devices on 4H SI SiC with (No. B1) and without (No. B7 did not undergo any etching) a GaN contact layer using the dry etching process. The photocurrent of the switching device with a GaN coating is almost an order of magnitude lower than that of the device without GaN at corresponding bias voltages. A possible reason is that the dry etching process degraded the channel surface by making it rougher and introducing more defects, although the optical absorption takes place in several tens of microns.

In conclusion, switching devices have been fabricated on 4H HP-SI SiC for high-power applications. A n^+-GaN subcontact was grown on SiC to decrease the contact resistance and eliminate contact damage under the cathode due to current crowding induced Joule heating. The relatively small hole mobility/diffusion constant is responsible for causing current crowding which is alleviated by inserting the GaN layer between the metal contact and high resistivity SiC. The

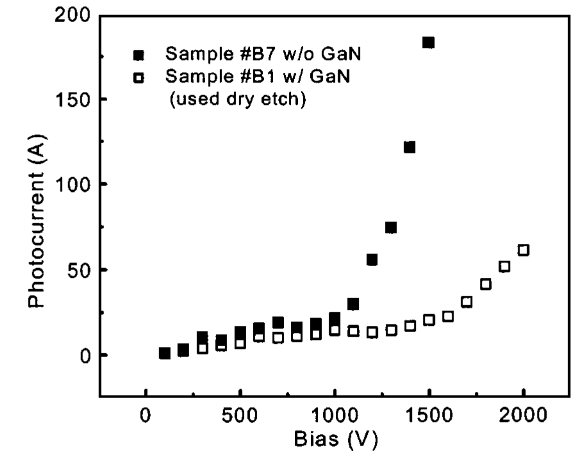

FIG. 4. Photocurrent of the 4H SI SiC switching device without (No. B7) and with (No. B1) GaN coating for various bias conditions. The GaN in channel area was removed by dry etching.

contact resistance and, therefore, the on-state resistance of the device was decreased by two orders of magnitude, and photocurrent efficiency was increased by two orders of magnitude with the GaN subcontact layer. Wet etching in a hot KOH solution was used for removing the GaN epilayer in the channel area, which proved to be more suitable than damage causing dry etching.

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