Ideal Ohmic contact to n-type 6H-SiC by reduction of Schottky barrier height

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We formed ideal Ti Ohmic contacts on an n-type 6H-SiC epitaxial layer by reducing Schottky barrier heights. The ideal contacts were realized by utilizing ideal SiC surfaces formed under processes that intend to lower the density of surface states. As the first process to form the ideal surfaces, SiC surfaces were flattened by oxidation followed by HF etching. Further, the ideal SiC surfaces in terms of passivation of surface states were formed by immersing the flat SiC surfaces in boiling water. Ti electrodes thus formed had Ohmic properties with excellent I–V characteristic linearity without the use of heavy doping and high-temperature annealing. © 1997 American Institute of Physics.

The formation of conventional Ohmic contacts by heavy impurity doping into semiconductors is difficult in SiC crystal that is a candidate material for semiconductor devices operating at high frequency, high temperature, or high power. Edmond et al. 1 reported that temperatures exceeding 1800 °C are required in thermal diffusion to fabricate a heavily doped SiC layer with a carrier concentration \( \geq 10^{18} \) cm \(^{-3} \). Impurity doping by ion implantation also proves difficult in fabricating such a layer because electrical dopant activity is low, about 5%, as estimated by Ruff et al. 2

The difficulty can be overcome only by the anneal of an electrode at high temperatures. 3, 4, 5 However, the anneal, typically at 1000 °C, conventionally used, restricts device fabrication and makes electrode morphology rough. The technique we propose here avoids heavy impurity doping and annealing in fabricating Ohmic contacts on an n-type 6H-SiC epitaxial sample.

In the Schottky model, 6 Ohmic contacts are formed as a result of zero Schottky barrier height when the metal work function \( \phi_m \) is smaller than the semiconductor’s electron affinity. This knowledge is of little practical use, 7 however, because of the Schottky barrier height \( \phi_{bn} \), not widely controlled by \( \phi_m \), present at the actual interface, i.e., Fermi level pinning. This pinning must be released to lower \( \phi_{bn} \) enough to make Ohmic contacts.

The Fermi level pinning is caused by interface states whose origin remains to be clarified; surface states such as dangling bonds preceding interface formation are suspected to relate strongly to interface states. In a practical metal/semiconductor system with Fermi level pinning, this pinning must be released to lower \( \phi_{bn} \) of 0.50 eV, indicating the change from Schottky to Ohmic properties. Fermi level pinning is released when \( S^0 = 1 \), but continues pinned to \( C \) when \( S^0 = 0 \). It is well known that the Fermi levels of metal/Si and metal/GaAs interfaces are almost pinned, where \( S^0 \) are 0.27 9 and 0.1, 10 respectively. When GaAs (100) surfaces are passivated by sulfur, \( S^0 \) increases to about 0.5. 11 In this example, technologically improved cleaning is significant, it is, however, still unknown what changes the Schottky barrier height and whether Fermi level pinning can be controlled systematically. We utilize recently developed chemical techniques 12, 13 that make an ideally monohydride-terminated surface with atomic surface flatness to reduce density of interface states. This makes interfacial electronic and electric properties easier to control. Reducing density of interface states, we formed ohmic contacts by lowering the Schottky barrier height on SiC crystal.

Three n-type 6H–SiC (0001) epitaxial samples with carrier concentration of about \( 5 \times 10^{17} \) cm \(^{-3} \) used in this study were degreased, then dipped in 5% HF solution to remove thin native oxide surface layers. An oxidized layer about 10 nm thick was then formed on two samples in a quartz tube furnace. The samples were then etched by dipping in 5% HF solution. One sample was then immersed in boiling water for 10 min; it is referred to as BW treatment hereafter. All samples were rinsed in deionized water after each surface treatment. In order to make low \( \phi_{bn} \) to n-type 6H-SiC crystal, Ti with low \( \phi_m \) of 4.33 eV, 14 was used as an electrode metal material. Electrodes 300 μm in diameter and 500 nm thick were formed by evaporating Ti onto the three samples through a metal mask using an E-gun system with a base pressure of about \( 3 \times 10^{-8} \) Torr. Each sample has over 20 electrodes. During deposition, the sample temperature was kept below 100 °C. Mg was evaporated as back electrodes after Schottky electrode formation because earlier back electrode formation contaminates the surface for the Schottky electrodes. For comparison, conventional Ni Ohmic electrodes were also fabricated by annealing a Ni-deposited sample at 1000 °C for 60 min in pure Ar. Al was also evaporated on a BW-treated sample.

5% HF-treated Ti electrodes exhibit rectification properties with \( \phi_{bn} \) of 0.81 eV ± 0.01 eV and an average ideality factor 15 of 1.22. After oxidation/HF etching, the I–V characteristic in the forward-biased region loses linearity with a reduced \( \phi_{bn} \) of 0.50 eV, indicating the change from Schottky to Ohmic properties. BW-treated Ti electrodes after oxidation/HF etching exhibit Ohmic properties with excellent linearity. Low-energy electron diffraction shows no spots for 5% HF-treated samples and 1×1 patterns for the oxidation/HF etching and BW-treated samples. This indicates that disordered layers were removed by our surface treatments. Contact resistivity \( \rho_c \) was estimated by measur-

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ing resistance between two Ti electrodes by varying the
distance between them.\textsuperscript{16} $\rho_c$ was $(6 \pm 1) \times 10^{-3}$
$\Omega \text{ cm}^2$—comparable to that of conventional Ni Ohmic elec-
trodes. The Ti electrode surface is flat, but high-temperature
annealing at $1000 ^\circ \text{C}$ has made the Ni electrode surface in-
homogeneous as shown in Fig. 1. For Al with a low $\phi_m$ of
4.28 eV\textsuperscript{14} almost the same as 4.33 eV for Ti, $\rho_c$ was $(4$
$\pm 1) \times 10^{-3}$ $\Omega \text{ cm}^{-2}$. This suggests that metals with low
$\phi_m$ tend to have the ohmic properties for the BW-treated
$n$-type 6H-SiC (0001) surface. The $I$–$V$ characteristics of Ti
electrodes on BW-treated SiC samples without the
oxidation/HF etching have rectification properties almost the
same $\phi_{bn}$ as in 5% HF treatment. This means oxidation/HF
etching and the BW treatment must be conducted sequen-
tially to form Ohmic Ti contacts.

The mechanism of Ohmic Ti interface formation is as
follows: In a heavily doped metal/semiconductor interface,
the depletion layer becomes thin enough for electrons to tun-
nel through the Schottky barrier, thus making electric prop-
erty Ohmic. The interface also becomes Ohmic property
when many band gap defect states are induced near the in-
terface. Both methods use current flowing through the
Schottky barriers. If Ohmic formation in our Ti contacts was
due to a thinned barrier or to defects, the Ohmic contacts
formed would be independent of the electrode metal ma-
terial. Au electrodes evaporated onto a BW-treated SiC
sample, however, exhibit a good Schottky property with a
leakage current below $10^{-9}$ A/cm$^2$, indicating that the two
methods above do not apply to the Ohmic Ti contacts.
Ohmic Ti contacts are, instead, formed due to current flow-
ing over a Schottky barrier lowered enough to show Ohmic
properties. Yu\textsuperscript{17} expressed $\rho_c$ of such Ohmic contacts
formed by lowering $\phi_{bn}$ as,

$$\rho_c = \frac{k}{q A^* T} \exp \left( \frac{q \phi_{bn}}{kT} \right),$$

(1)

where $k$ is the Boltzmann constant and $A^*$ is the Richardson
constant. Using experimentally obtained $\rho_c = 6 \times 10^{-3}$
$\Omega \text{ cm}^2$, $\phi_{bn}$ of Ohmic Ti contacts is estimated from Eq. (1)
to be 0.38 eV with $A^* = 194.4$ A/cm$^2$K$^2$.\textsuperscript{18}

Data\textsuperscript{18–22} reported on the metal/$n$-type 6H-SiC system
and our data are plotted in Fig. 2. Slope parameter $S^\circ$
estimated by fitting reported data using the least-squares method
is about 0.25, indicating that the Fermi level of usual metal/
SiC interfaces is almost pinned. $\phi_{bn}$ of the 5% HF-treated
Ti/SiC interface is in the pinning regime. $\phi_{bn}$ of our BW-
treated Ti/SiC interface is about 0.4 eV lower than that of the
pinned interface, however, suggesting that the degree of
Fermi level pinning can be changed by surface treatment.

The mechanism of lowering $\phi_{bn}$ at the Ti/SiC interface
by surface treatment is as follows: Dangling bonds on a Si
(111) surface immersed in boiling water are known to be
terminated by monohydrides.\textsuperscript{13} This monohydride termina-
tion is occurred by back-bond oxidation of surface Si atoms,
followed by etching of oxidized Si atoms by OH group in
boiling water, as discussed by Watanabe \textit{et al.}\textsuperscript{23} Since the
SiC (0001) surface has the same structure as that of a Si
(111) surface in terms of Si termination and (111) crystallo-
graphic direction, monohydride termination is possible on
our SiC surface. On the other hand, Elsbergen \textit{et al.}\textsuperscript{24}
reported that oxygen of 0.6±0.1 monolayers is present on the
SiC surface dipped in pH-modified buffered HF. Starke et al. measured the SiC surface dipped in NH$_4$F by Auger electron spectroscopy and high-resolution electron energy loss spectroscopy. They reported that the surface has a bit of oxygen and is partially terminated by OH group. From the above discussions, there are some possibilities on surface terminators of the BW-treated SiC surface. The resultant interface that forms on the surface, however, is ideal in terms of electronic passivation because the Schottky barrier at the interface is reduced.

The Schottky barrier height is also lowered by oxidation/HF etching. On a Si (111) surface, Ohishi et al. found that the surface is oxidized layer by layer by suppressing oxidation speed using low-pressure oxygen. The oxidation process removes interface steps and kinks, making the interface atomically flat. Here, horizontal oxidation at steps and kinks in the Si/SiO$_2$ interface is dominant, compared to vertical diffusion of oxygen. The oxidation rate of 6H-SiC is very slow, implying that oxygen atoms migrate horizontally relatively easily.

In conclusion, we formed ideal SiC Ohmic contacts by making the SiC surface atomically flat.