Electrical Characteristics of Rectifying Polycrystalline Silicon/Silicon Carbide Heterojunctions

J.P. HENNING, K.J. SCHOEN, M.R. MELLOCH, J.M. WOODALL, and J.A. COOPER, JR.

School of Electrical and Computer Engineering and NSF-MRSEC for Technology-Enabling Heterostructure Materials, Purdue University, West Lafayette, IN 47907-1285

This paper presents a study of the rectifying properties of heavily doped polycrystalline silicon (polysilicon) on 4H silicon carbide (4H-SiC). Current properties and barrier heights were found using analysis of the heterojunction. This revealed that Schottky analysis would be valid for the large barrier height devices. Isotype and an-isotype devices were fabricated on both p-type and n-type SiC and the electrical characteristics were investigated using capacitance vs voltage measurements, current vs voltage measurements (I-V), and temperature I-V measurements. Extraction of the barrier height, built-in potential, and Richardson constant were made and then compared to theoretical values for the heterojunction. Temperature I-V measurements demonstrated that the current transport mechanism is thermionic emission, confirming the validity of the Schottky diode model. The I-V characteristics show near ideal diode rectifying behavior and the capacitance-voltage characteristics show ideal junction space charge modulation for all polysilicon/SiC combinations. These experimental results match well with heterojunction band-offset estimated barrier heights and demonstrate that the barrier height of the polysilicon/4H SiC interface may be controlled by varying the polysilicon doping type.

Key words: Heterojunction diode, Schottky diode, silicon carbide

INTRODUCTION

Previous works in the area of SiC contacts and heterojunctions have focused on metal-semiconductor contacts[1] and crystalline semiconductor-semiconductor heterojunctions.[2] Recent reports have shown that InAs/GaP lattice mismatched heterojunctions form nearly ideal rectifying contacts.[3] In addition, nanocomposite materials form rectifying contacts to 6H SiC.[4] The potential for forming quality rectifying heterostructure contacts to SiC with non-crystalline semiconductor materials would appear to be good. Polycrystalline silicon (polysilicon) on 4H SiC is a candidate heterojunction for this type of rectifying contact.[5]

The formation of a polysilicon contact on SiC has several potential advantages. First, the contact should be very stable since both polysilicon and SiC are inherently stable materials. Consequently, the possibility of reaction at the heterojunction interface is reduced. Second, the electrical properties of the contact may be easily controlled by varying the polysilicon doping concentration and type. Third, the processes used to form these contacts are straightforward and commonly used by the semiconductor industry. Here we report the electrical characteristics of polysilicon on 4H SiC heterojunctions.

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DISCUSSION

The heterojunctions fabricated are n-type polysilicon/n-type SiC (nN), p-type polysilicon/n-type SiC (pN), p-type polysilicon/p-type SiC (pP), and n-type polysilicon/p-type SiC (nP). The n-type 4H SiC samples are Si face and have a 5 μm thick epilayer with nitrogen doping of approximately 3×10^{16} cm^{-3}. The p-type 4H SiC samples are Si face and have a 5 μm thick epilayer with boron doping of approximately 6×10^{15} cm^{-3}. The SiC material was acquired from Cree Research, Inc. About 600 nm of polysilicon was deposited onto the SiC samples by low-pressure chemical vapor deposition (LPCVD) at 630°C. A heavily doped spin-on glass was used to dope the polysilicon either n-type (phosphorous) or p-type (boron). The spin-on glass dopant was driven in for 30 min at a

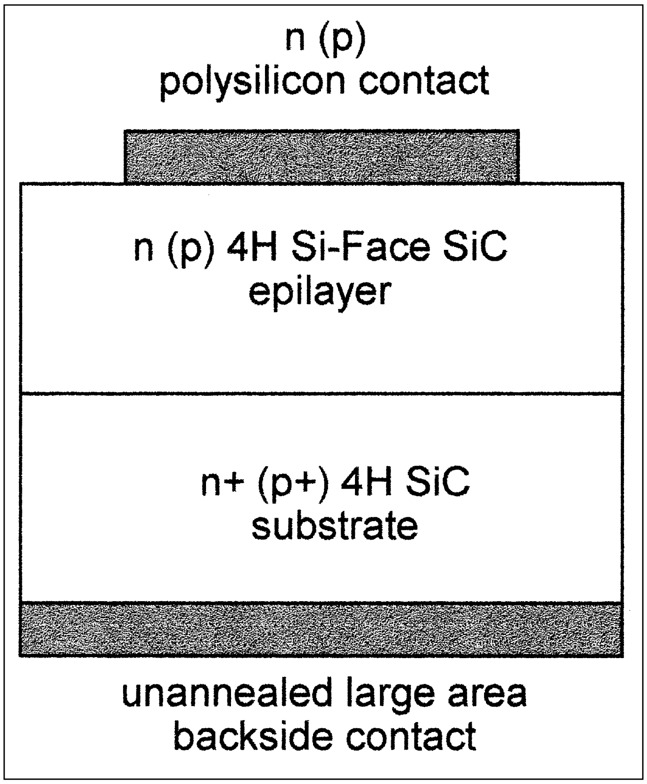

Fig. 1. Polysilicon/4H SiC contact device structure.

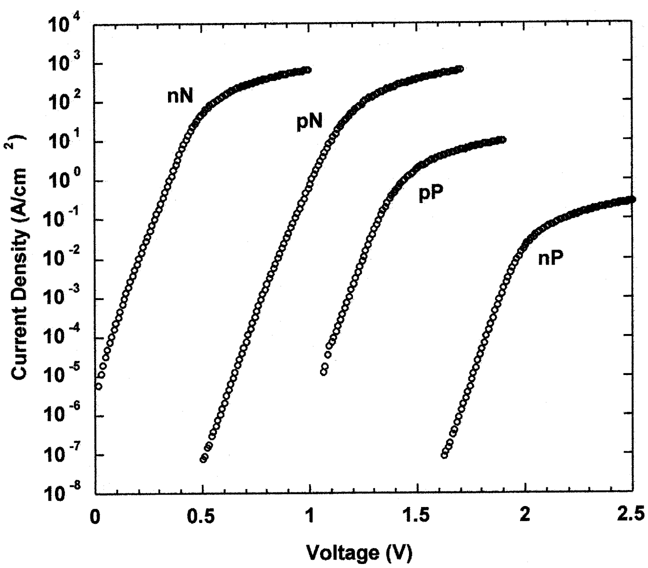

Fig. 2. Forward bias I-V characteristics of nN, pN, pP, and nP contacts on 4H SiC.

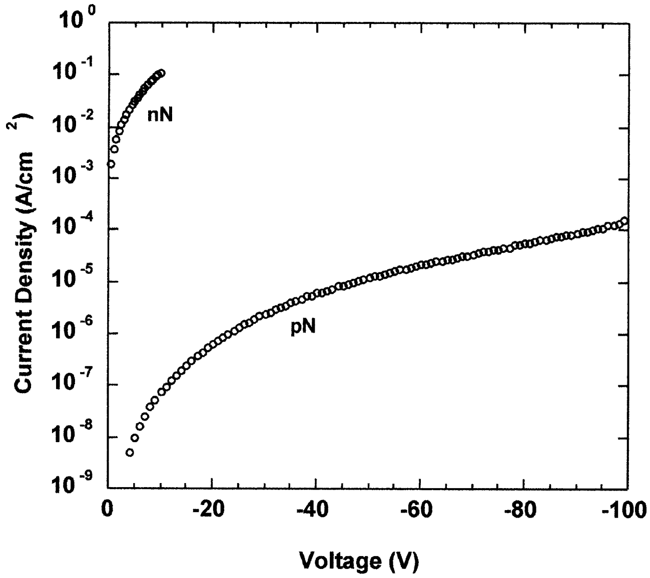

Fig. 3. Reverse bias I-V characteristics of nN and pN polysilicon contacts on 4H SiC.

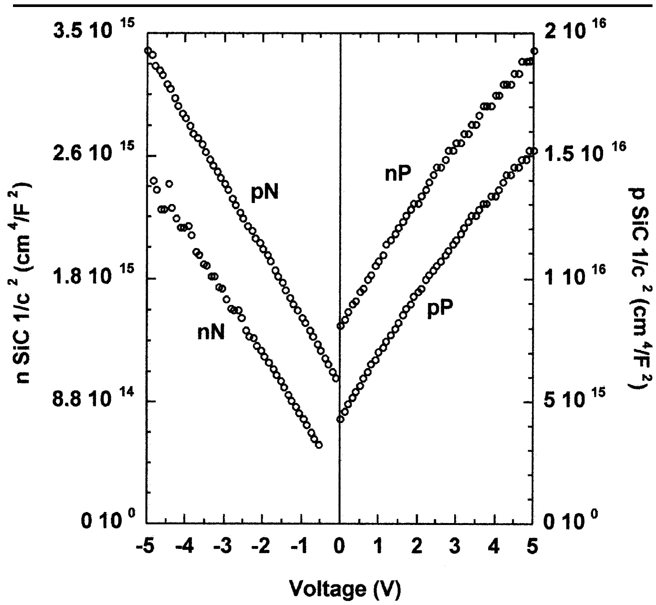

Fig. 4. C-V characteristics of nN, pN, pP, and nP polysilicon contacts on 4H SiC.

temperature of 1000°C. Circular contacts were patterned by photolithography and reactive ion etching (RIE) of the polysilicon. Device fabrication was completed by depositing unannealed large area backside contacts to the SiC substrate (aluminum for n-type and nickel for p-type). A diagram of the device structure is shown in Fig. 1.

Current-voltage (I-V) measurements of the contacts were taken by directly probing the individual circular contacts varying in diameter from 40 to 400 μm, and measuring the I-V characteristics with an HP 4145 parameter analyzer. Capacitance-voltage (C-V) measurements were also taken by wafer probing and measuring the C-V characteristics with an HP 4274 LCR meter. Temperature data was taken using a hot chuck in which the wafer temperature was elevated.

The room temperature forward bias I-V characteristics for the nN, pN, pP, and nP polysilicon/4H SiC contacts are shown in Fig. 2. The electrical characteristics show near ideal diode rectifying behavior for all polysilicon on SiC combinations at room temperature. The contacts all showed excellent linearity on a log current vs voltage plot with five to eight decades of linearity and current densities as high as 600 A/cm^2 at room temperature. The eventual roll-off of the I-V

Table I. Summary of the Theoretical Heterojunction Band Offset Barrier Heights, Experimental I-V, and Experimental Values by Activation Energy Method Along with Theoretical and Experimental Values of the Richardson Constant

Type	Measured A*	Theoretical A*	Activation Energy Measured ϕ_b	Theoretical ϕ_b	I-V Measured ϕ_b
p^+N	39.0	146	1.18	1.5	1.21
n^+P	32.7	72	2.67	2.8	2.63
p^+P	3.43	72	1.56	1.7	1.61

Table II. Summary of Theoretical Heterojunction Band Offset Calculated Values, Experimental I-V Values, and Experimental C-V Values for Polysilicon/4H SiC Contacts

	I-V			C-V		
Type	n	ϕ_B (eV)	Theoretical ϕ_B (eV)	N_B (cm^{-3})	V_{bi} (V)	Theoretical V_{bi} (V)
n^+N	1.17	0.72	0.4	3.2×10^{16}	0.70	0.3
$p^+ N$	1.21	1.26	1.5	3.0×10^{16}	2.08	1.4
p^+P	1.18	1.58	1.7	5.7×10^{15}	1.70	1.5
n^+P	1.09	2.31	2.8	5.5×10^{15}	3.09	2.6

characteristics is due to series resistance. The series resistance is due to the nonalloyed back side contacts and of the substrates. Because of the lower mobility and lower room temperature activation of dopants, the diodes on the p-type substrates exhibit higher series resistance.

The room temperature reverse bias I-V characteristics for the nN and pN contacts are shown in Fig. 3. The reverse leakage current of the nN contact is substantially larger than that of the pN conact. Although they vary from theoretical,[6] this corresponds with the lower turn-on voltage of the nN contact. The reverse bias I-V characteristics of the pP and nP contacts were also measured; however, the current levels of both were below noise level of the measurement system ($<10^{-9}$ A/cm^2) for reverse biases of 100 V and less.

The $1/C^2$-V plots for the diodes are shown in Fig. 4. The $1/C^2$-V plots show good linearity, characteristic of a single sided abrupt junction.

The I-V and C-V characteristics of these heterojunctions have been analyzed as Schottky contacts. It has been shown that abrupt heterojunctions with offset energy bands may be characterized using Schottky barner analysis.[7] It seems logical that the isotype heterojunctions (nN and pP) can be analyzed as Schottky barrier contacts since they are majority carrier devices, but it is less obvious that the anisotype heterojunctions (pN and nP) can also be analyzed as Schottky barrier contacts. Consider that the theoretical conduction and valence band off-sets are significant ($\Delta E_C = 0.4$ eV and $\Delta E_V = 1.7$ eV) and the diffusion length in the polysilicon is small, it is plausible to suspect thermionic emission is the dominant current-limiting mechanism. This approach is validated by the results of the activation energy measurements. When extraction of the activation energy agrees with the theoretical barrier height, this suggests the current mechanism to be thermionic emission, and thus exhibiting Schottky characteristics.

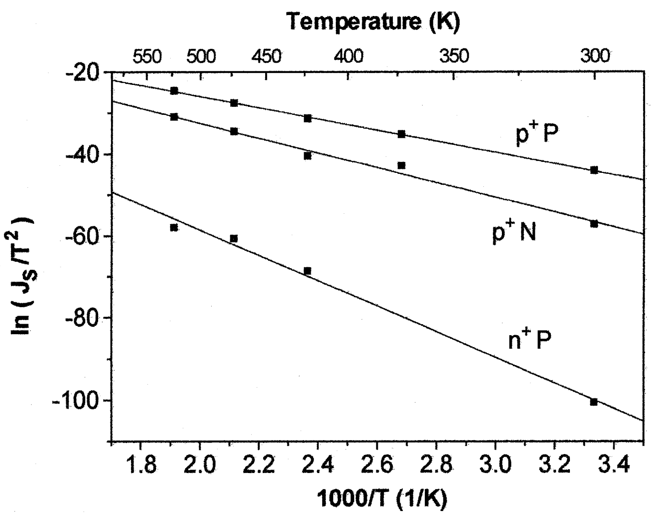

Fig. 5. Plot of the results of the activation energy measurements.

The polysilicon/SiC I-V characteristics were therefore analyzed using the equation for the thermionic emission current of a Schottky contact. The relationship between barrier height, applied voltage, and current density is,[8]

$$J = A^{**}T^2 e^{-q\phi_B/kT}\left(e^{qV/nkT} - 1\right) = J_S\left(e^{qV/nkT} - 1\right) \quad (1)$$

Where A** is the modified Richardson's constant (146 A/cm^2K^2 for n-type SiC[9] and 72 A/cm^2K^2 for p-type SiC)[10] and ϕ_B is the contact barrier height. The barrier heights, which are determined from the linear portion of the forward bias I-V characteristics in Fig. 2, are listed in Table I.

If the $\ln(J/T^2)$ vs 1/T is plotted for a single bias point, or for J_s, the Richardson constant and the ϕ_b at T = 0°C or activation energy, can be extracted. Figure 5 shows the plots of $\ln(J_s/T^2)$ vs 1/T used to extract the activation energy ($E_A = q\phi_b$). It has been shown that when the slope is of the value (ϕ_b-V), the dominant current mechanism is that of thermionic emission.[11] When a recombination current is present, the slope decreases because of an additional recombination term with an ideality factor of n = 2. Table I shows the theoretical values of these parameters and the measured values for the p^+N, n^+P, and p^+P diodes. Temperature data for the n^+N diode could not be used due to series resistance limiting the low voltage turn on of this diode, thus preventing extraction of the temperature dependent reverse saturation current. There is fairly good agreement with the barrier height extracted from the I-V characteristics and those extracted from the activation energy indicating that thermionic emission is the dominant current mechanism. The Richardson constant does show significant variation. However, the Richardson constant is embedded in a log function as seen in

$$\ln\left(\frac{J}{T^2}\right) = \ln(A^*) + \frac{q}{k}\left(\frac{V}{n} - \phi_b\right)\frac{1}{T} \tag{2}$$

So a small error in determining ln(A*) from the intercept in Fig. 5 will result in a much larger error in the determination of A*.

The heterojunctions have theoretical Schottky barrier heights based on the differences between the Fermi level in the polysilicon and the conduction band of the SiC for N type and valance band for P type SiC. This is assuming the polysilicon is heavily doped and the Fermi level to be in the valence or conduction band. A value of 3.7 eV for χ_{4HSiC} was used along with $\chi_{Si} = 4.1$, $E_{G,Si} = 1.12$, and $E_{G,4HSiC} = 3.23$ eV.[6,9] The C-V characteristics were analyzed using the equation for the capacitance of a Schottky contact (same as for a one-sided abrupt junction). The relationship between built-in potential, applied voltage, and capacitance is,[8]

$$\frac{1}{C^2} = \frac{qN_B}{2\varepsilon_s}\frac{1}{(V_{bi} - V)} \tag{3}$$

Where N_B is the doping concentration, V_{bi} is the built-in potential, and V is the applied voltage.

Values for V_{bi} and N_B were extracted from the C-V data and are indicated in Table II. Differences in the theoretical built-in potential and the C-V measured built-in potential trends may be due to the effect of surface states on the C-V measurements.

SUMMARY

Polysilicon may be used to form nearly ideal rectifying contacts to 4H SiC. These contacts have been shown to have Schottky behavior. The polysilicon doping type and concentration can be used to vary the barrier height and the resulting barrier heights are in good agreement with predicted theoretical values. Therefore, polysilicon on 4H SiC contacts hold promise as a device structure for forming stable heterojunctions.

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