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Fabrication of boron-carbide/boron heterojunction devices

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We have succeeded in the fabrication of a boron–carbide/boron diode on an aluminum substrate, and a boron–carbide/boron junction field effect transistor. Our results suggest that with respect to the approximately 2 eV band gap pure boron material, 0.9 eV band gap boron–carbide (B_5C) acts as a *p*-type material. Both boron and boron–carbide (B_5C) thin films were fabricated from single source borane cage molecules using plasma enhanced chemical vapor deposition (PECVD). Epitaxial growth does not appear to be a requirement. © *1996 American Institute of Physics.* [S0003-6951(96)00311-8]

Boron and boron–carbide devices have been sought since 1959[1] but only recently has the fabrication of these devices been realized.[2,3] Such devices would have applicability in a wide number of harsh conditions; they should be resistant to corrosive, high temperature, and mechanically abrasive environments. Because of the large neutron capture cross section, these materials could potentially be used as devices in radioactive environments as well.[4]

This letter details the fabrication of several working boron/B_5C heterojunction devices. This achievement builds upon the recent success in construction of boron–carbide/*n*-Si(111) heterojunction diodes.[5,6] We have demonstrated that boron–carbide/Si(111) heterojunction diodes can be fabricated from *closo*-1,2,-dicarbadodecaborane ($C_2B_{10}H_{12}$; orthocarbonane) by using synchrotron radiation-induced chemical vapor deposition (SR-CVD)[5,6] and plasma-enhanced chemical vapor deposition (PECVD).[2,3,5–7] Pure boron films also had been deposited on silicon from *nido*-decaborane ($B_{10}H_{14}$; decaborane) by using SR-CVD.[8,9] In an effort to fabricate a more sophisticated device, we made a transistor in our PECVD system. We made a diode directly on an aluminum substrate to demonstrate that a silicon interface is not essential for fabrication of a boron–carbide device. The use of plasma-enhanced chemical vapor deposition (PECVD) provides a means for fabricating boron and boron–carbide thin films successfully in a high resistivity form.[2,3] This work addresses some of the issues associated with making devices of increasing complexity from boron–carbide.

The aluminum substrates were polycrystalline, and the silicon substrates were (111), *n* type. Both were chemically etched and cleaned prior to insertion *in vacuo* and set on the lower electrode. The substrates were further cleaned by Ar^+ bombardment at 300 mTorr, 40 W and annealed at 400 °C in the vacuum system. Deposition was carried out in a custom-designed parallel plate 13.56 MHz radio-frequency plasma-enhanced chemical vapor deposition (PECVD) reactor described previously.[3,7]

Using our established CVD sources, boron–carbide/boron multilayers were deposited on aluminum and silicon. Figure 1 shows the schematic cross-sectional view of the fabricated multilayer devices. Decaborane was used to form a pure boron film on the substrates. Boron–carbide (B_5C) films were then deposited on the pure boron layer from orthocarborane. The purity of the orthocarborane and decaborane was determined by infrared (ir), nuclear magnetic resonance (NMR), and mass spectral measurements (purity 98%), and compared with literature values,[10] and less than 1% of the metacarborane and paracarborane isomers were found to be present. The decaborane was sublimed to separate the source material from cellite (a stabilizer) and other impurities.[10]

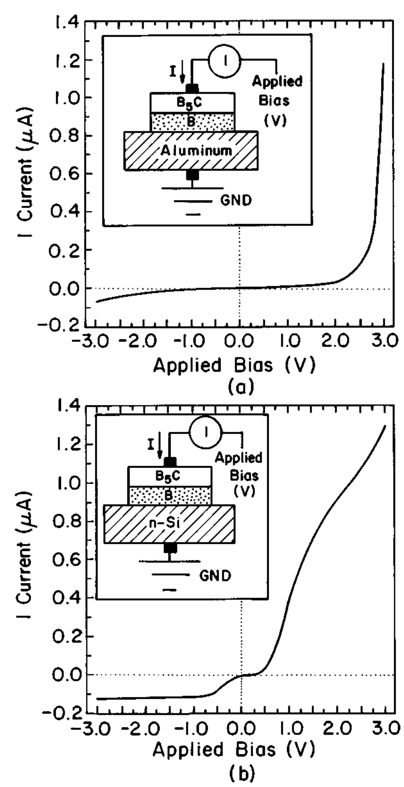

FIG. 1. Diode *I–V* characteristics of (a) boron–carbide/boron/aluminum and (b) boron–carbide/boron/*n*-Si(111). Each insert shows schematic cross-sectional view of its structure along with the characteristics of the electrical wire connections.

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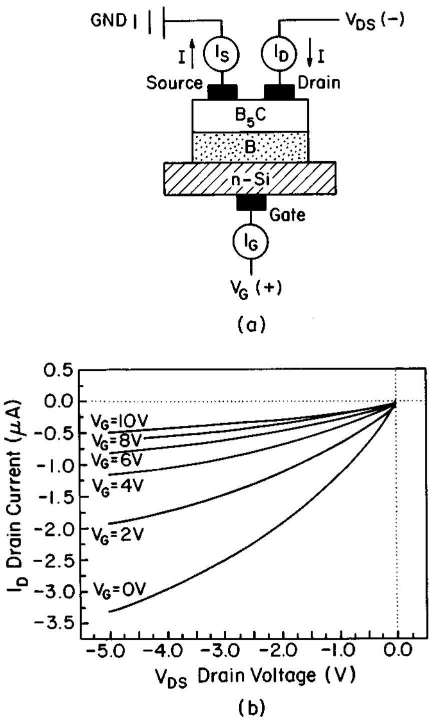

FIG. 2. (a) The schematic cross-sectional geometry of fabricated boron–carbide junction field-effect transistor (JFET). The schematic also illustrates electrical wire connections as well as polarities of each applied bias. (b) Transistor characteristics of I_D (drain current vs V_{DS}). Gate voltage, V_G, was applied from 0 to 10 V by 2 V steps.

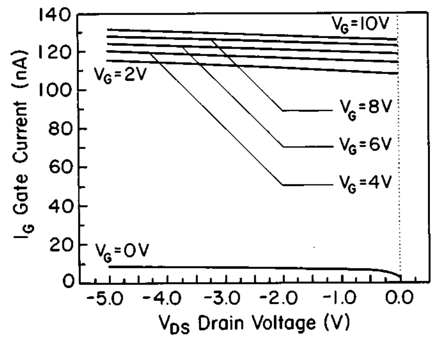

FIG. 3. The transistor characteristics of I_G (gate current) vs V_{DS} for the device shown in Fig. 2. Note that, relative to Fig. 2, the currents are small.

The diode I–V characteristics of a B_5C/boron/aluminum structure are seen in Fig. 1(a). Although not shown here, a boron/aluminum structure exhibits an ohmic characteristic, which leads to the conclusion that a junction exists between the B_5C boron and boron with the B_5C acting as the *p*-type material. The I–V diode characteristics of a B_5C/boron/*n*-type silicon structure are seen in Fig. 1(b). In this case, the boron/*n*-type silicon structure, which is not shown, exhibits a diode characteristic with the boron acting as a *p* layer with respect to the *n*-type silicon. This result, combined with results of Fig. 1(a) and the boron/aluminum structure, indicate that the B_5C/B/*n*-type silicon structure consists of two diodes in series oriented in the same direction. This is borne out by the observed diode curve in Fig. 1(b). Furthermore, neither structure exhibits the classical exponential diode behavior in the forward direction. This type of behavior is similar to the previously reported boron–carbide/*n*-type Si(111) heterojunction.[2,3] We have demonstrated that boron–carbide thin film on *n*-type Si(111) heterojunction diodes are insensitive to the morphology of the film.[6] The semiconductor properties of the material do not appear to depend upon crystallite size and the extent of long-range order growth of similar material on both aluminum and Si(111) is anticipated.

The fabricated boron–carbide/boron/silicon multilayer device can be employed as a junction field effect transistor (JFET). Figure 2(a) shows the schematic diagram of the measurement circuit, while Fig. 2(b) shows the drain current versus drain voltage, with the source at ground, as a function of the gate voltage. Based on the characteristics of Fig. 1(b), the gate is biased positive, while the drain is swept through negative voltages, each with respect to the grounded source. As the gate voltage is increased, the magnitude of the drain current decreases for any given value of drain voltage, which is the expected behavior for a JFET. It should be pointed out that the device does not saturate, nor does it completely cut off. This is probably a result of the fact that this is a single junction device, and the junction is relatively far removed from the source and drain region.

Figure 3 is the gate current versus drain voltage as a function of gate voltage. When combined with Fig. 2(b), this clearly indicates that the leakage current is less than 10% of the drain current.

We have already compared diodes fabricated from boron carbide with crystallites of different sizes (30, 100, and 240–340 Å).[6] While the ideality factors of these diodes do differ, similar rectifying diodes were fabricated[6] to the ones shown in this work. We believe that this insensitivity to crystal grain size and the clear evidence that a device can be fabricated on very different substrates provides some evidence that epitaxial growth is not a determining issue in the fabrication of devices made with this microcrystalline or polycrystalline semiconductor material.

In summary, we have succeeded in the fabrication of a boron–carbide/boron junction field effect transistor on *n*-type (111) silicon. Our results suggest that with respect to the pure boron material, B_5C acts as a *p*-type material. Both boron and B_5C thin films were fabricated from single source borane cage molecules using PECVD. We have also fabricated a working B_5C/boron diode on aluminum.

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