P-type 3C-SiC nanowires and their optical and electrical transport properties†

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We report for the first time the fabrication of p-type SiC nanowire field-effect transistors (FETs) using an individual Al-doped 3C-SiC nanowire with a single crystalline structure. The Raman spectroscopy of the as-grown p-type wire indicates that the linewidth and peak intensity of LO-phonon bands are sensitive to temperature variations.

Semiconductor nanowires (NWs) are of great importance in the fabrication of nanoelectric and nanophotonic devices and have shown substantial promise for integrated nanosystems.1 A distinctive feature of semiconductor NWs, which is responsible for much of their success, involves the ability to grow NWs with reproducible electronic properties, including the controlled incorporation of n-type and/or p-type dopants.1–3 This is crucial for future NW design, since it can change the conductivity, mobility and carrier type of the semiconductor crystals.4 Based on this concept, a new form of doping called complementary doping has been proposed for the incorporation of both p- and n-type dopants in a single material system.1 Extensive attempts have previously been made to apply this method to silicon (Si),2 zinc oxide (ZnO),5 indium phosphide (InP)5 and gallium nitride (GaN)1 NWs and these attempts have contributed to creating substantial opportunities for exploring new nanodevices. For instance, p-type and n-type Si NWs have been used to assemble p–n diodes, bipolar transistors and complementary inverters,5 while a p–n diode formed from the p- and n-type InP NWs can function as nanoscale near-infrared light-emitting diodes (LEDs).6 These previous results are really fascinating and show the attractive prospects of the field and, hence, complementary doping in other materials is being pursued.

Silicon carbide (SiC) NWs are one of the most promising nanoscale building blocks and have been extensively studied in recent years. This is due to them being an important wide bandgap semiconductor with a high electron mobility and breakdown field strength, as well as high thermal conductivity, excellent mechanical properties and chemical stability. It has been proven that these versatile and even exclusive features are suited to widespread applications in high-temperature/high-voltage electronics, short-wavelength optics and field-emission devices.7 To date, tremendous efforts have been devoted to the synthesis of SiC nanostructures via various methods.8–11 However, most of the obtained nanostructures are pure SiC12 and some of them are intrinsically n-type unintentionally doped materials.13–15 Although developing p-type SiC NWs as a material for advanced semiconductor electronic device applications is believed to be extremely important, since it can enable the exploration of a new family of SiC nanodevices and circuits based on complementary materials, such as Junction FET(JFET) and p–n junction diodes, so far no p-type 3C-SiC NWs have been reported. One reason is that producing p-type NWs still remains a challenge due to their high electron density. Herein, we report the successful synthesis and the optical and transport properties of intentionally doped p-type 3C-SiC NWs, where Al is used as the dopant.

Fig. 1a shows a low-magnification scanning electron microscopy (SEM) image of the as-synthesized SiC NWs grown on the graphite substrate. It shows that these NWs have a mean lateral size of 200 nm and an approximate length of up to tens of micrometres, with an aspect ratio of ca. 30. Fig. 1b is a typical TEM image under low-magnification, clearly disclosing that the 3C-SiC NWs have an almost uniform diameter throughout their entire length without any tips or any attachments of catalytic droplets. The observation of more than 30 nanowires suggests that they all have a similar shape. Fig. 1c presents a typical XRD pattern of the resultant products, suggesting that 3C-SiC is the only crystalline phase (JCPDS Card No. 29-1129). The strong, sharp peaks indicate that the obtained nanowires are well crystallized. The SAED pattern (inset of Fig. 1b), which is identical over the entire wire, further suggests that the wires are 3C-SiC with a single-crystalline nature and possess a perfect structure without defects. Clear evidence for the incorporation of Al is shown in the typical EDS spectrum recorded from the NWs in Fig. 1d. It indicates that the wires mainly consist of Si and C.
but also contain a very small amount of Al and O. The O element is ascribed to a small amount of the surface oxide on the thin amorphous layer of the nanowires, while the observed Cu comes from the copper grid used to support the TEM sample. The atomic ratio of Si to C, which is within the experimental limit, is close to 1:1, suggesting that the crystalline nanostructure is SiC. Both EDS and XRD results imply that synthesized nanostructures are Al-doped 3C-SiC NWs. The intentional Al doping concentration is measured to be ~2 atom% with a uniform spatial distribution within the wires.

To fabricate FETs based on an individual Al-doped 3C-SiC NW, the NWs in ethanol solution were deposited onto a degenerately doped n-type Silicon wafer capped with a 300 nm silicon dioxide (SiO2) layer. The electron-beam (e-beam) lithography was used to define pairs of metal electrodes on the SiO2/Si substrate, followed by metal deposition of Ni/Au (10/200 nm) by thermal evaporation. The obtained FET is shown in the lower inset of Fig. 2. The electrical current ($I_{ds}$) versus the drain–source voltage ($V_{ds}$) measurements at various gate voltages ($V_g$) was performed using a Keithley 4200 semiconductor parameter analyzer under ambient conditions (Fig. 2).

In a typical device, the wire shows nearly linear and symmetric $I_{ds}$–$V_{ds}$ curves over the entire $V_{ds}$ range, indicating good ohmic contacts of metal stacks to the NW. This is primarily due to Ni forming a stable conducting silicide with a low Schottky barrier on the SiC surfaces. Another reason is the large contact area. The calculation based on the line at $V_g = 0$ V yields a two-terminal resistivity of 5.8 Ω cm, which is derived from $\rho = V_{ds}\pi r^2/I_{ds}L$, where $r = \sim 100$ nm is the wire radius and $L = 3.2$ μm is the length of the active channel of the NW. A typical $I_{ds}$–$V_g$ curve of the device at $V_{ds} = 0.5$ V (the upper inset of Fig. 2) shows that the effective drain–source current decreases by a factor of 1.5 as $V_g$ increases from ~10 to 10 V. This result clearly indicates that the majority of carriers in the NW are p-type. Meanwhile, it also shows that the measured conductance of the wire is less sensitive to $V_g$, suggesting the device has relatively weak gating effects. It is known that 3C-SiC NWs are intrinsically n-type materials. However, previous reports show that the energy level of Al is about 0.26 eV and lies above the valence band edge of SiC. Nevertheless, the latter strongly indicates that Al doping of SiC can induce additional shallower acceptor states in the band structure, while compensating for the native donor states. Therefore, the incorporation of intentional Al dopant into the SiC NW can produce the as-grown p-type materials. From the above $I_{ds}$–$V_g$ curve, a peak transconductance ($g_m$) of 12 nS at $V_{ds} = 0.5$ V is obtained. Assuming that the channel width equals the diameter of the NW (~200 nm), the normalized $g_m$ for the FET is estimated to be ~60 nS μm$^{-1}$. The hole mobility ($\mu$) can then be estimated by using $\delta I_{ds}/\delta V_g = \mu C/L^2 V_{ds}$ where $C$ is the capacitance, which can be given by $C = 2\pi \varepsilon_0 L/\ln(2h/r)$, where $h = 300$ nm is the dielectric thickness of SiO2. The hole carrier concentration can be obtained using the expression $I = pq\mu E A$, where $p$ is the hole carrier concentration, $E$ is the electric field and $A$ is the area of the NW. The estimated hole carrier density and the field-effect carrier mobility of the Al-doped SiC NW FET were determined to be ~1.7 × 10$^{17}$ cm$^{-3}$ and ~6.4 cm$^2$(V·s$^{-1}$) respectively. Since the as-grown SiC NWs have nearly perfect single crystallinity, the influence of the intrinsic defects on the hole carrier concentration should be much less. The confinement of carriers into a one dimensional NW on a nanoscale can thus greatly increase the hole carrier concentration and also contribute to the low resistivity. However, the value of the field-effect carrier mobility is found to be 2–3 times lower compared to that expected in the p-type 3C-SiC film and those of 4H-SiC, p-channel, state-of-the-art, planar, metal oxide semiconductor FETs (MOSFET) devices. For instance, the carrier mobility for the monocrystalline thin film of 3C-SiC with the same hole carrier density as our grown SiC NWs is measured to be ~20 cm$^2$(V·s$^{-1}$) while the value for a MOSFET device reaches ~15.6 cm$^2$(V·s$^{-1}$). The low mobility value could be explained by the relatively high hole concentration, the one dimensional nanoscale carrier confinement, enhanced scattering in the
carrier density up to 3.8 × 10^{19} \text{ cm}^{-3}$. The observed weak gating effect of the device might be due to weaker electrostatic gating effects, lower capacitances and weak gate coupling caused by the rough nanowire surface having a bamboo-like morphology (Fig. 1b).

In order to investigate how the Al doping affects the optical properties of the p-type 3C-SiC NWs, a typical Raman spectrum from a single NW at different temperatures was recorded with a wave laser (632.8 nm) as the excitation source (Fig. 3). It shows that the as-grown NWs exhibit two broad absorption bands. Their maximum values appear at approximately 772 and 910 cm\(^{-1}\) at room temperature, whereas at a lower temperature of \(-190\) °C these values shift to 782 and 922 cm\(^{-1}\). The two peaks are the dominate features of the crystalline structure of 3C-SiC and correspond to the modes of transverse (TO) and longitudinal optical (LO) phonons, respectively.\(^{15}\) Both peaks display small red shifts (10–12 cm\(^{-1}\)) with increasing temperature as a result of the effects of thermal expansion, lattice-mismatch-induced strain and anharmonic coupling to other phonons.\(^{20}\)

More interestingly, the curve-fitting spectrum reveals that the temperature increase has no effect on the peak intensity or the width of the TO-phonon bands (\(\sim 100\) cm\(^{-1}\)), while it reduces the absorption of the LO mode and broadens to its full-width at half-maximum from \(\sim 40\) to \(\sim 60\) cm\(^{-1}\). These results have never been reported elsewhere and the reasons for them are as follows. Firstly, previous results have shown that TO-phonon damping is almost independent of the carrier density up to \(\sim 1 \times 10^{19} \text{ cm}^{-3}\) (the hole carrier density of the SiC wire is \(\sim 1.7 \times 10^{17} \text{ cm}^{-3}\)).\(^{21}\) Thus, the peak intensity and width of the TO-phonon bands are almost not influenced by temperature, although the active carriers concentration and phonon numbers in the NWs increase with temperature. Secondly, the carrier density and the spatial distribution of the dopants are related to the line shape of the LO phonon plasmon-coupled (LOPC) modes.\(^{21,22}\) For the doped samples studied, Al doping of SiC generates free hole carriers in NWs. Therefore, light can excite oscillations of these free carriers (plasmons) that can couple to the longitudinal optical phonons leading to the LOPC mode. Thirdly, the linewidth of the LO mode is known to be reciprocally related to the phonon lifetime of the decay process.\(^{20}\)

The Raman spectroscopy performed on a single Al-doped 3C-SiC wire shows that the linewidth of the LO-phonon bands increases and the peak intensity of the LO mode becomes lower at high temperatures.

In summary, p-type FETs based on an individual Al-doped 3C-SiC wire have been fabricated. A typical device exhibits a high hole carrier concentration of \(\sim 1.7 \times 10^{17} \text{ cm}^{-3}\), a low mobility of \(\sim 6.4 \text{ cm}^2/(\text{V} \cdot \text{s})\) and a weak gating effect. The Raman spectroscopy performed on a single Al-doped 3C-SiC wire shows that the linewidth of the LO-phonon bands increases and the peak intensity of the LO mode becomes lower at high temperatures.

Notes and references