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Quantum confinement and coherence in a two-dimensional electron gas in a carbon-face 3*C*-SiC/6*H*-SiC polytype heterostructure

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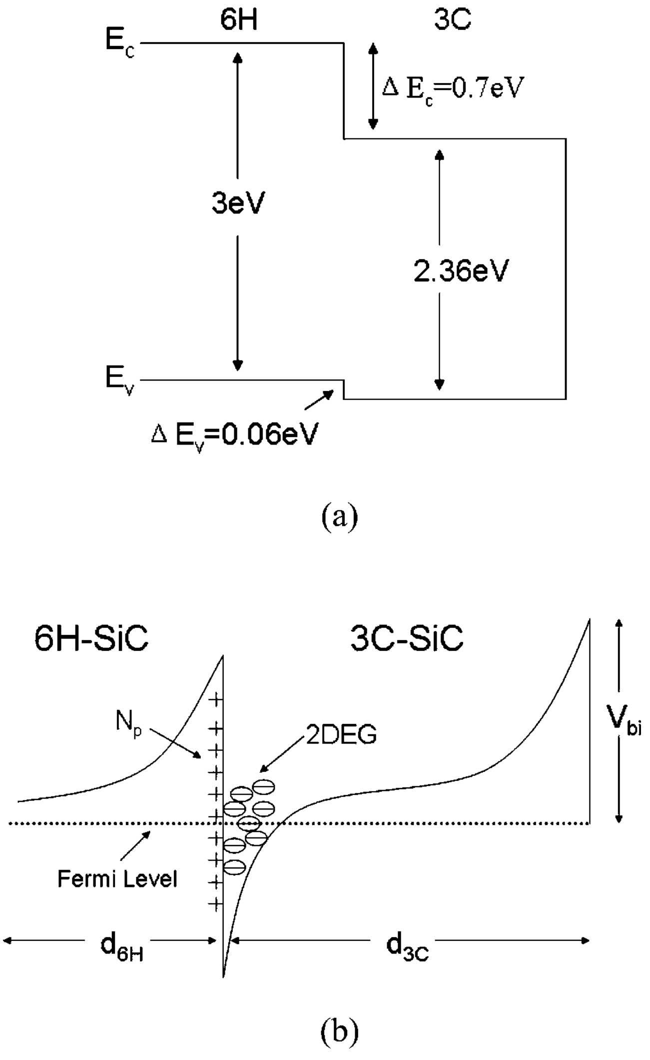
We report the observation of the quantum coherence in a two-dimensional electron gas (2DEG) at a C-face 3*C*-/6*H*-SiC polytype heterostructure. Electronic confinement and coherence were observed at 1.5 K and high magnetic fields, indicating the presence and confinement of a 2DEG. The measured mobility of the 2DEG is 2000 cm^2/V s and the electron sheet density is $2.7\times 10^{12}/\text{cm}^2$. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3126447]

Silicon carbide (SiC) has been studied intensively due to its potential for enabling high voltage, high power, and high frequency devices.[1] This semiconductor material has over 250 polytypes. The common polytypes are 3*C*-(cubic), 4*H*-(hexagonal), and 6*H*-SiC. The hexagonal polytypes exhibit spontaneous polarization while the cubic polytype does not.[2] The 3*C* polytype is lattice matched in the ⟨0001⟩ plane to 6*H*-SiC within <0.1%. In addition these polytypes are thermally matched to <0.1% over the entire range of measurements and sample preparation temperatures.[3] This matching enables a class of chemically homogeneous heterostructures formed only by an abrupt change in crystal structure and or stacking, rather than the traditional method of using an abrupt change in composition, such as GaAs/AlGaAs. Such heterostructures could also be more reliable and controllable than composition-based heterostructures.

3*C*-SiC (bandgap, E_g=2.36 eV) and 6*H*-SiC (E_g=3.0 eV) have a large conduction band offset (0.7 eV). In addition hexagonal 6*H*-SiC exhibits a strong spontaneous polarization similar to GaN/AlGaN.[4] This affords the possibility of forming a quantum well at the junction between these two polytypes. The spontaneous polarization leaves a fixed positive charge on the C-face of ⟨0001⟩ 6*H*-SiC, electrostatically inducing a mirror electron charge, which is then confined by the band offset. To obtain a two-dimensional electron gas (2DEG), 3*C*-SiC must be grown on C-face hexagonal SiC.[4–7] The band structure[8] of 3*C*-SiC and 6*H*-SiC is shown in Fig. 1.

Such a SiC polytype heterojunction has been both theoretically proposed and experimental observed.[3–6] Previous measurements have established the persistent conductivity of this structure at low temperatures, although the confinement within a 2DEG was less clear.[6] In this paper, we provide direct evidence for the confinement of the 2DEG in the form of quantum Hall and Shubnikov–de Haas (SdH) measurements in a C-face 3*C*-/6*H*-SiC heterostructure at low temperature and in magnetic fields up to 10 T.

Our SiC epilayers were grown on the C-face semi-insulating 6*H*-SiC substrates by vertical cold-wall chemical vapor deposition. Silane, propane, and HCl were used as reactants in a hydrogen carrier gas. An unintentionally doped ($\sim 2\times 10^{17}/\text{cm}^3$ *n*-type as determined by capacitance-voltage measurements) 200 nm thick 6*H*-SiC buffer layer and a 3*C*-SiC heterolayer were grown at 1350 °C and 200 Torr at a growth rate ~0.8 μm/h. Figure 1 shows the diagram of the band offsets for this heterostructure. Phosphorus-implanted contact well regions were activated at 1350 °C (Ref. 9). The wafers were then fabricated in Hall bar geom-



(a)

(b)

FIG. 1. (a) Band diagram for 6*H*-SiC and 3*C*-SiC and (b) schematic illustrating the electrostatics of the 3*C*-/6*H*-SiC heterostructure at equilibrium, where N_p is the positive polarization charge at the C-face of SiC.

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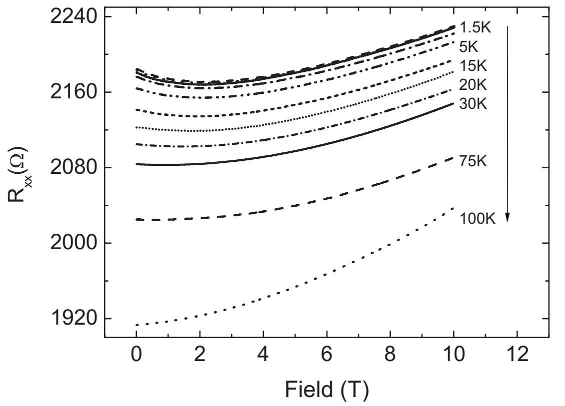

FIG. 2. R_{xx} as a function of the magnetic field up to 10 T at different temperatures.

etry with high-purity Ni Ohmic contacts alloyed at 1000 °C. Typical Hall bar geometries with lengths of 100 μm and widths of ~5 μm were used.

Magnetotransport measurements were performed over the magnetic-field range 0–10 T and temperatures 1.5–100 K, as shown in Figs. 2 and 3. In Fig. 2 we plot the variation in the longitudinal resistance R_{xx} from 1.5 to 100 K. At low temperatures, when the magnetic field is below 1 T, we observe negative magnetoresistance, which can be identified with weak localization in the disordered semiconductor system. At higher temperatures, electron scattering increases and reduces the extent to which this localization phenomenon is observed.

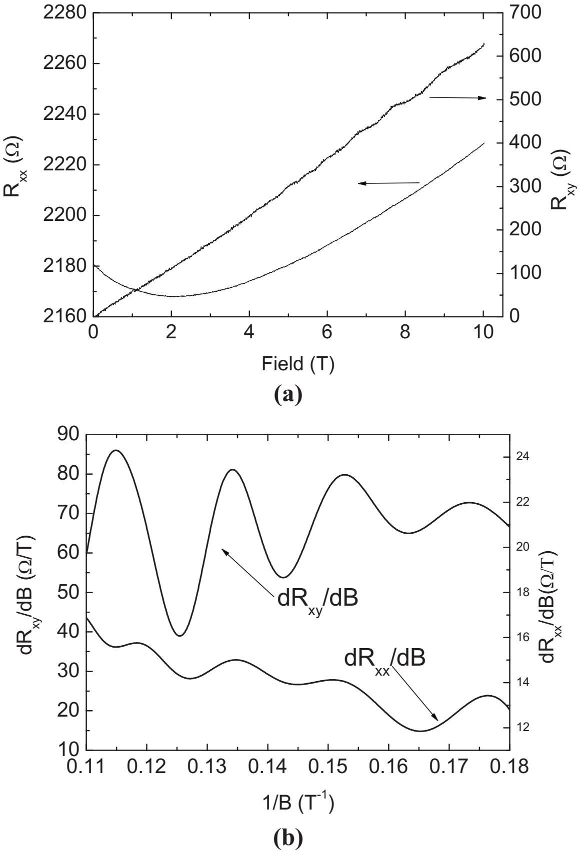

FIG. 3. (a) Longitudinal magnetoresistance R_{xx} and transverse magnetoresistance R_{xy} in 3*C*-/6*H*-SiC heterostructures as a function of magnetic fields oriented normal to the heterointerface at 1.5 K. (b) $d(R_{xy})/dB$ and $d(R_{xx})/dB$ as a function of $1/B$ after FFT smoothing.

Figure 3(a) shows the measured R_{xx} and transverse resistance R_{xy} as a function of magnetic field at 1.5 K. Quantum Hall plateaus (QHPs) in R_{xy} can be observed. However, in R_{xx}, the amplitude of the oscillations is weak. By taking the derivative of R_{xy} and R_{xx} with respect to magnetic field, we can clearly identify the periods the QHPs in R_{xy} and SdH oscillations in R_{xx} as a function of $1/B$ [Fig. 3(b)]. The QHP and SdH oscillations indicate the presence of a well-confined 2DEG.[10,11]

Observation of the QHPs requires that the thermal energy broadening kT and the scattering-induced energy broadening $\hbar/\tau$ be smaller than the Landau level spacing $\hbar\omega = \hbar eB/m^*$, where k is Boltzmann's constant, T is the temperature, τ is the momentum relaxation time, B is the magnetic field, and m^* is the effective mass.[12] The condition $\hbar\omega > \hbar/\tau$ is equivalent to $\mu B > 10^4$ cm^2 T V s, where μ is the carrier mobility $\mu = e\tau/m^*$. Figure 3 shows that the threshold magnetic field to observe the QHPs is ~5 T. Based on the condition for the mobility, this provides an estimate $\mu \sim 2000$ cm^2/V s.[13] This value is the mobility of 2DEG itself. So it is higher than the one gotten from Ref. 6 which is the mobility of both 2DEG and bulk material.

Similarly, the 2DEG sheet density can be obtained from the periodicity of the QHPs, which is periodic in $1/B$ (Ref. 14).

$$N_{\mathrm{2DEG}} = \frac{2e}{hP(1/B)}, \qquad (1)$$

where $P(1/B)$ is the period of the oscillation with respect to $1/B$ and h is Planck's constant. From Eq. (1) and Fig. 3, we calculate the sheet density of the 2DEG to be $(2.7 \pm 0.2) \times 10^{12}/\mathrm{cm}^2$. This agrees well with capacitance-voltage measurements of the carrier density in these heterostructures.[15]

In summary, we report the observation of the quantum coherence of a 2DEG in a SiC heterostructure. Clear quantum confinement and coherence were observed at 1.5 K and high magnetic field in a C-face 3*C*-/6*H*-SiC heterostructure, which indicates the presence and confinement of a 2DEG. The mobility of the 2DEG is ~2000 cm^2/V s and the electron sheet density is $2.7 \times 10^{12}/\mathrm{cm}^2$. These results show that the 2DEG formed in 3*C*-SiC/6*H*-SiC heterostructures is comparable to the 2DEG in AlGaN/GaN structures in both sheet density and mobility, with the added benefits of lattice/thermal matching, making the SiC polytype heterostructure a promising candidate for high electron mobility transistors.

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