Room temperature ballistic transport in InSb quantum well nanodevices

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We report the room temperature observation of significant ballistic electron transport in shallow etched four-terminal mesoscopic devices fabricated on an InSb/AlInSb quantum well (QW) heterostructure with a crucial partitioned growth-buffer scheme. Ballistic electron transport is evidenced by a negative bend resistance signature which is quite clearly observed at 295 K and at current densities in excess of 106 A/cm2. This demonstrates unequivocally that by using effective growth and processing strategies, room temperature ballistic effects can be exploited in InSb/AlInSb QWs at practical device dimensions. © 2011 American Institute of Physics. [doi:10.1063/1.3668107]

Harnessing ballistic transport effects in low-dimensional structures at room temperature (RT) is a promising avenue for developing innovative nanoelectronic devices for applications including logic circuits, biosensing, and high-density data storage. Carbon-based systems such as carbon nanotubes (CNTs)1,2 and graphene3 have received considerable attention owing to their extraordinarily long mean free path (l0) at RT (<50 µm in CNTs) and high current carrying capability, but the realization of very-large-scale-integration compatibility remains a fundamental challenge. In this respect, high mobility III-V semiconductors are technologically relevant. Several groups4,5 have explored ballistic switching and rectifying concepts in InGaAs/InP quantum wells (QWs), where l0 ≈ 150 nm at 295 K. The operating efficiency of such devices is closely linked to the ratio of l0 to the critical device dimension and is limited to ~20% due to the small value of l0 in such systems. Electron mobilities of μe ≈ 45 000 cm2/Vs are routinely achieved in InSb/AlInSb QWs at 295 K—the largest reported of any III-V system.6 For a typical electron density n0 ≈ 6 × 1011 cm−2, this corresponds to l0 = hfell/t ≈ 550 nm (where fe2 = (2πn0)1/2). Considerable advantages would be afforded by pursuing such device concepts in this system; however, to-date, the RT operation of InSb QW nanodevices has been inhibited by excessive buffer layer leakage currents.7

In this letter, we report the magnetotransport properties of mesoscopic devices fabricated on an InSb/AlInSb QW with a partitioned buffer layer (PBL) scheme8 designed to suppress the parasitic leakage currents, which demonstrate remarkably clear ballistic transport at 295 K as a result.

The sample used is a 15-nm modulation doped InSb/AlIn−xSb QW grown by MBE onto a GaAs (001) substrate with a PBL scheme (growth details are found elsewhere)8. A 15-nm pseudomorphic Al0.3In0.7Sb layer is incorporated 300 nm below the QW to provide a potential barrier to electrons and holes, thermally generated in the bulk of the buffer layer, from diffusing to the ohmic contact region. In this way, the effective electrical thickness of the buffer layer is reduced from 3 µm to 300 nm. The electron density and mobility of the QW at 295 K are n0 = 7.31 × 1011 cm−2 and μe = 41 500 cm2/Vs (l0 = 586 nm), as deduced from high magnetic field measurements on 40-µm-wide (reference) Hall bridges.8 Mesoscopic cross structures of various sizes were fabricated using e-beam and optical lithography and shallow (100 nm etch depth) reactive ion etching (RIE) in a CH3/H2 (1:8) gas mixture. Magnetotransport measurements were performed in perpendicular magnetic fields (B) up to 7.5 T at various temperatures using standard AC and DC measurement techniques. The sidewall depletion width, wdep, was estimated from the dependence of the two-terminal conductance (G2T) (B = 0) of several devices on the physical lead width at 160 K to be wdep ≈ 120 nm (not shown).

We have investigated ballistic electron transport at elevated temperatures by studying the bend resistance Rb = (V4 − V3)/I21 (see Fig. 1 insets). If B = 0, a large proportion of electrons injected from lead 1 are ballistic, those with large forward momentum are transmitted directly to the opposite lead 3. This raises the potential of lead 3 with respect to lead 4, generating a negative bend resistance (NBR). A small magnetic field deflects the electron beam away from lead 3 into one of the side leads causing the NBR to decay. The resulting dip in Rb(B) (centered on B = 0) is a clear signature of ballistic transport. The NBR anomaly has previously not been observed above 200 K in InSb/AlInSb devices.7

The results for Rb(B) obtained from a symmetric cross with physical lead width w0 = 550 nm (5550) and an asymmetric cross width w0 (w1) = 360 (660) nm (A360) between 160 K and 295 K are shown in Figs. 1(a) and 1(b), respectively (device geometries are shown in the insets). At 160 K, a distinct NBR is observed in both devices with an amplitude and full width at half maximum (FWHM) that remains approximately constant up to 240 K. Remarkably, the NBR feature persists up to 295 K indicating significant ballistic transport.
electron transport in the QW. This result demonstrates that the parasitic effects of parallel conduction in the buffer layer have been substantially suppressed by wafer design, and moreover, that the processing strategy has not degraded $\mu_e$ to the point that all carriers are diffusive as is reported in InAs/AlSb devices.\(^9\) The NBR feature is superposed on a background resistance ($R_{bg}$) that is approximately constant ($\approx 100 \, \Omega$) below 240 K and rises with increasing temperature such that $R_B(0)$ is no longer negative. Nevertheless, ballistic coupling of leads 1 and 3 is evident by the persistent dip at $B = 0$. This background will be discussed further in comparison to theoretical modeling. A secondary feature of the bend resistance data is the asymmetry of the magnetic field response. The geometrical origin of this is confirmed by measurements of the resistance $R'_B = (V_1 - V_2)/I_{34}$ which satisfies very closely the reciprocity relation $R_B(B) = R'_B(-B)$, as shown for device A360 by the dashed line in Fig. 1(b).

Measurements of the Hall resistance, $R_{H} = (V_4 - V_2)/I_{34}$, were also performed. The electron densities of the mesoscopic devices ($n_{mes}$) were estimated from the Hall slope, at fields ($\approx 0.5$ T) where ballistic anomalies are absent, to be $n_{mes} = 5 \times 10^{11}$ cm$^{-2}$ and $n_{mes} = 4.5 \times 10^{11}$ cm$^{-2}$ at 295 K (160 K), for S550 and A360, respectively.

To gain further insight into the microscopic properties of the devices, we have performed extensive numerical quantum transport calculations of $R_B(B)$ using a tight-binding code which combines the Green’s function techniques of Baranger et al.\(^{10}\) and Sanvito et al.\(^{11}\) Some effects of finite temperature were simulated using a simple energy-averaging technique that takes into account the Fermi distribution.\(^{10}\) We consider two possible types of disorder in the devices: elastic scattering from impurities and from the sidewalls (shown to be important in our previous work). Impurity scattering was modeled with Anderson site-disorder; the on-site energies of the tight-binding Hamiltonian were chosen from an interval $[-U, U]$ with uniform probability.\(^{10}\) Sidewall scattering was taken into account by introducing a boundary roughness characterized by a mean amplitude ($\Delta$) and correlation length ($\Lambda$) after Akera et al.\(^{13}\) We use $\Delta = 5 \, \text{nm}$ (deduced from atomic force microscopy of the lateral etched surface) and consider the three limits: $\Lambda \ll \lambda_F$, $\Lambda \sim \lambda_F$, and $\Lambda \gg \lambda_F$, where $\lambda_F = 2\pi/k_F$ is the Fermi wavelength. Electron-phonon scattering is not included in this simple model; however, as we will show, the impurity scattering model captures the essential features of momentum scattering within the channel.

Figures 2(a) and 2(b) shows the energy-impurity averaged bend resistance curves (lines), $\langle R_B(B) \rangle$, for device S550 with varying disorder compared to the experimental data at 160 K (symbols). Note that we have used the experimental $w_{mes}$ and the effective electrical lead widths $w_{eff} = w - 2w_{dep}$ in the absence of disorder $\langle R_B(B) \rangle$ has zero background resistance, and an NBR that is both broader and larger in amplitude ($\langle \Delta R_B \rangle$) than observed experimentally. Finite $R_{bg}$ is, therefore, clear evidence of disorder in the experimental devices. The quantum calculations provide confirmation that the observed low-field ($< 1$ T) characteristics of $R_B(B)$ are determined almost entirely by scattering in the channel rather than by scattering at the boundaries: (1) Calculations with only sidewall scattering yield $\langle \Delta R_B \rangle$ up to 10 times greater than the experimental data due to enhanced electron collimation\(^{14}\) (not shown for clarity); (2) $R_{bg}$ is sensitive to the strength of impurity scattering [Fig. 2(a)] but is relatively insensitive to the presence, or type, of boundary roughness [Fig. 2(b)]; and (3) A comparison of $\langle \Delta R_B \rangle$ with and without surface roughness [Fig. 2(b)] to experiment suggests little enhancement from diffuse collimation in the present devices. Indeed, good agreement with the experimental data is found for the $\langle R_B(B) \rangle$ curves with smooth boundaries ($\Delta = 0$) and $U = 0.32$ (solid line Fig. 2(b)). Similar results were found for device A360 [Fig. 2(c)]. Note that the assumption of smooth...
sidewalls is consistent with large $w_{dep}$ due to electrostatic screening of the exterior sidewall roughness.

The effective channel mobility ($\mu_{eff}$) for a given disorder can be obtained from calculations of $G_{2F}$ for single leads of varying length ($l'$) in diffusive limit where the relation $G_{2F}(l') = n_{max}\mu_{eff}(l'/l')$ is valid. The disorder corresponding to the solid curves in Figs. 2(b) and 2(c), yield $\mu_{eff} \approx 45,000$ cm$^2$/Vs. Comparing this value obtained from 0 K quantum calculations to that of the reference sample at 160 K, we find $\approx 30\%$ reduction in the former case, suggesting that some degradation has occurred due to the nanofabrication process.

We now discuss the operation of our devices in the high bias, nonequilibrium transport regime relevant for nonelectronic applications where large signals are required. In principle, hot-ballistic electron transport is limited by LO phonon emission ($h\nu_0 = 25$ meV in InSb), but at 295 K the thermal broadening of the electron distribution is already rather large ($\approx 26$ meV), and thus, hot electron effects should be less acute.

The forward bias $IV$ characteristic of device A360 ($w_{on} \approx 130$ nm) at 295 K is shown in Fig. 3(a). A distinct nonlinearity is observed at high bias current, but note that the differential resistance is positive over the entire range ($R_D$) and the nonequilibrium regime where $G_{2F}$ is essentially energy independent for $E_F$ and $E_D$. Synonymous with the above is a broadening of the NBR ($\Delta R$) due to LO phonon emission, and the turnover characteristic of device $I_{12}$, with increasing $I_{12}$ [see inset to Fig. 3(a)]. Since the FWHM ($B_{FWHM}$) is proportional to $k$, the broadening is a direct indication of the excess kinetic energy ($\Delta E \approx eV_{34}$) gained in the nonequilibrium regime where $k \propto k_F(1 + \Delta E/E_F)^{1/2}$ and $E_F$ is the Fermi energy. Likewise, if we assume $\Delta R_b(\Delta E, T) \propto \exp[-w_{on}/(1 + \Delta E/E_F)^{1/2}T(\Delta E, T)]$, the Fermi velocity and momentum-scattering time, respectively, the behavior for $I_{12} < 25 \mu A$ can be understood by an increasing electron velocity, and $\Delta (\Delta E, T)$ that is essentially energy independent for $\Delta E < h\nu_0$. The turnover occurs at a voltage $eV_{34} \approx h\nu_0$ [see Fig. 3(a)], at which point injected electrons have sufficient energy to scatter by phonon emission, and $\Delta (\Delta E, T)$ is reduced substantially. This is consistent with the theory of optical phonon scattering, but contrary to previous reports at low temperature, the observed hot electron effects are considerably less acute and demonstrate that RT ballistic effects persist without decay up to $eV_{34} \approx h\nu_0$.

Finally, we can consider these devices as examples of quasi-ballistic Hall probes. The magnetic sensitivity is given by the noise-equivalent-field (NEF) $B_{NEF} = V_{I_{12}}/I_{12}$, where $V_n$ is the voltage noise and $R'$ the Hall coefficient ($\theta/T$). For device A360, we have $R' = 20 \Omega$ and $R' = 1300 \Omega$ at 295 K, giving $B_{NEF} \approx 500$ nT/$\sqrt{Hz}$ for a bias current of $25 \mu A$ (where we have used the Johnson noise limit $V_n = 4k_B T R' I_{12}$). This sensitivity is considerably greater than the previous reports of sub-micron Hall probes, and magnetoresistance sensors at RT, demonstrating that although not yet optimized, the ballistic cross structures we report here are highly competitive and hold significant promise for future high resolution RT sensors.

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