Room temperature ballistic transport in InSb quantum well nanodevices

A. M. Gilbertson,1,a) A. Kormányos,2 P. D. Buckle,3 M. Fearn,2 T. Ashley,4 C. J. Lambert,2 S. A. Solin,1,5 and L. F. Cohen1

1Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom
2Department of Physics, Lancaster University, Lancaster LA1 4YB, United Kingdom
3Department of Physics and Astronomy, Cardiff University, Cardiff CF24 CAA, United Kingdom
4School of Engineering, University of Warwick, Coventry CV4 7AL, United Kingdom
5Center for Materials Innovations and Department of Physics, Washington University in St. Louis, Missouri-63130, USA

(Received 7 October 2011; accepted 18 November 2011; published online 12 December 2011)

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 10^8 A/cm^2. 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 (l_0) 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 l_0 ≈ 150 nm at 295 K. The operating efficiency of such devices is closely linked to the ratio of l_0 to the critical device dimension and is limited to ~20% due to the small value of l_0 in such systems. Electron mobilities of μ_e ≈ 45 000 cm^2/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 n_e ≈ 6 × 10^{11} cm^{-2}, this corresponds to l_0 = h k_F μ_e/e ≈ 550 nm (where k_F = (2πn_e)^{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/Al_0.3In_0.7_Sb QW grown by MBE onto a GaAs (001) substrate with a PBL scheme (growth details are found elsewhere).8 A 15-nm pseudomorphic Al_0.3In_0.7_Sb 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 n_e = 7.31 × 10^{11} cm^{-2} and μ_e = 41 500 cm^2/Vs (l_0 = 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 CH_3/H_2 (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, w_{dep}, was estimated from the dependence of the two-terminal conductance (G_{2T}) (B = 0) of several devices on the physical lead width at 160 K to be w_{dep} ≈ 120 nm (not shown).

We have investigated ballistic electron transport at elevated temperatures by studying the bend resistance R_B = (V_4 - V_3)/I_{21} (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 R_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 R_B(B) obtained from a symmetric cross with physical lead width w_0 = 550 nm (5550) and an asymmetric cross width w_0 (w_1) = 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 at room temperature.
The NBR feature is superposed on a background. We use (not shown for some effects of finite and Sanvito 2(b) and 2(c)).

We consider two possible types of disorder in the devices: (1) Calculations with only sidewall scattering $R_{bg}^\langle \rangle$ (lines) with varying disorders compared to the experimental data at 160 K (symbols). (a) S550 with smooth sidewalls and impurity potential as labeled. (b) S550 with $U=0.32$ and sidewall roughness as labeled. (c) A360 with $U=0.25$ and smooth sidewalls. Fluctuations are due to interference effects that are not fully averaged out. Horizontal dashed lines indicate $R_{bg}=0$. (A corner rounding radius $r=120 \text{ nm}$ and lead length $l'=1.7 \text{ cm}$ was used in all cases, see inset.)

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 $\Lambda >> \Lambda_F$, where $\lambda_F = 2\pi/\hbar k_F$ 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 $<R_{bg}^\langle \rangle>$ for device S550 with varying disorder compared to the experimental data at 160 K (symbols). Note that we have used the experimental $n_{mes}$ and the effective electrical lead widths $w_{eff}$ ($w_{eff} = w - 2 w_{dep}$). In the absence of disorder $<R_{bg}^\langle \rangle>$ has zero background resistance, and an NBR that is both broader and larger in amplitude ($<\Delta R_{bg}>$) 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 ($<1 \text{ T}$) characteristics of $R_{bg}$ are determined almost entirely by scattering in the channel rather than by scattering at the boundaries: (1) Calculations with only sidewall scattering yield $<\Delta R_{bg}>$ up to 10 times greater than the experimental data due to enhanced electron collimation (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 $<\Delta R_{bg}>$ 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 $<R_{bg}^\langle \rangle>$ 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
and 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 $G_{2\tau}$ for single leads of varying length ($l'$) in diffusive limit where the relation $G_{2\tau}(l') = n_{me}(\mu_{eff}l'/l)$ 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 0K quantum calculations to that of the reference sample at 160K, 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 nanoelectronic applications where large signals are required. In principle, hot-ballistic electron transport is limited by LO phonon emission ($h\omega_0 = 25$ meV in InSb), but at 295K 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 ($w_{0eff} \sim 130 \text{ nm}$) at 295K 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 due to the diffuse background. Figure 3(b) shows the nonmonotonic dependence of the DC NBR amplitude $\Delta R_n$ on $I_{21}$. Synonymous with the above is a broadening of the NBR 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 $\Delta R_n(\Delta E,T)$ $\propto \exp[-w_{0eff}/\nu_F(1 + \Delta E/E_F)^{1/2}(\tau(\Delta E,T))]$, where $\nu_F$ and $\tau(\Delta E,T)$ are the Fermi velocity and momentum-scattering time, respectively, the behavior for $I_{21} < 25 \mu$A can be understood by an increasing electron velocity, and $\tau(\Delta E,T)$ that is essentially energy independent for $\Delta E < h\omega_0$. The turnover occurs at a voltage $eV_{34} \approx h\omega_0$ [see Fig. 3(a)], at which point injected electrons have sufficient energy to scatter by phonon emission, and $\tau(\Delta E,T)$ 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 $eV_{34} \approx h\omega_0$.

Finally, we can consider these devices as examples of quasi-ballistic Hall probes. The magnetic sensitivity is given by the noise-equivalent-field (NEF) $B_{NEF} = V/I_{12}R'$, where $V_n$ is the voltage noise and $R'$ the Hall coefficient ($\Omega/T$). For device A360, we have $R_T = 20$ k$\Omega$ and $R' = 1390$ $\Omega/T$ 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 $V_n = 4k_B T R_{34}$). 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.

This work was supported by the UK EPSRC under Grant No. EP/F065922/1. S.A.S. is also supported by the U.S. NSF under Grant No. ECCS-0725538 and NIH under Grant No. 1U54CA11194201, and has a financial interest in PixelEXX, a start-up company whose mission is to market imaging arrays.

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