Fabrication of closely spaced, independently contacted Electron-Hole bilayers in GaAs-AlGaAs heterostructures

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We describe a technique to fabricate closely spaced electron-hole bilayers in GaAs-AlGaAs heterostructures. Our technique incorporates a novel method for making shallow contacts to a low density (<10\(^{11}\) cm\(^{-2}\)) 2-dimensional electron gas (2DEG) that do not require annealing. Four terminal measurements on both layers (25nm apart) are possible. Measurements show a hole mobility \(\mu_h > 10^5\) cm\(^2\)V\(^{-1}\)s\(^{-1}\) and an electron mobility \(\mu_e > 10^5\) cm\(^2\)V\(^{-1}\)s\(^{-1}\) at 1.5K. Preliminary drag measurements made down to T=300mK indicate an enhancement of coulomb interaction over the values obtained from a static Random Phase Approximation (RPA) calculation.

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Advances in MBE growth techniques over the last two decades have made possible fabrication of closely spaced double quantum well structures. Such 2×2DEG (double 2D electron gas) and 2×2DHG (double 2D hole gas) structures have enabled the most definitive measurements of quantities like electron-electron scattering rates, compressibility etc. where many-body effects play a crucial role. Several interesting possibilities have been discussed about the formation of correlated phases with superfluid-like properties, in electron-hole bilayers, when the interlayer spacing becomes comparable to the electron-hole Bohr radius (~15nm in GaAs). The \(\nu=1\) bilayer state in 2×2DEG and 2×2DHG emulates a true electron-hole bilayer in certain ways. Recent experiments on these have shown a remarkable enhancement of the Hall drag. However compared to these structures, an electron-hole bilayer is much more difficult to fabricate and contact. If modulation doping is used to populate both quantum wells, a bend bending of 1.5V (bandgap of GaAs) over ~15nm must exist in the barrier layer. The built-in electric field of ~10^6V/m, must arise self-consistently from the ionised dopants and the free carriers. Devices in which simultaneous accumulation of electrons and holes in close proximity has been demonstrated, reduce the amount of band-bending required by introducing a discontinuity in the electrochemical potential across the barrier. Considering the novel states which are thought to exist in the electron-hole Bohr radius (~1nm), the study of the formation of correlated phases with superfluid-like properties, in electron-hole bilayers, when the interlayer spacing becomes comparable to the electron-hole Bohr radius (~15nm in GaAs) is of considerable importance.

In this letter, we describe an electron-hole device (see Fig.1) with a 25nm Al\(_{0.3}\)Ga\(_{0.7}\)As barrier. Both quantum wells (QW) are in the “inverted” configuration. The lower hole QW is doped. Electrons accumulate in the upper QW under biasing. We use a novel scheme of shallow contacts using a heavily doped (8×10^18 cm\(^{-3}\)) Si GaAs/InAs capping layer to contact the electron layer. Doped InAs pins the Fermi level above the conduction band at the surface. Any metal which adheres well to the surface (e.g. Ti/Au) forms an ohmic contact to the region below. A nearly flatband condition is maintained in the region between the contact and the 2DEG, allowing a “non-spiking” ohmic contact to the 2DEG. These contacts do not require annealing and have been found to work down to 2DEG densities in the low 10^10 cm\(^{-2}\) range till T<300mK. Unlike ion-implanted contacts, a high temperature anneal (~800°C) is not required to activate them.

Diffused Au-Be alloy is used to contact the hole layer and a carefully controlled isolation etch is introduced between each pair of n and p contacts (Fig.1,2). The etch removes sufficient GaAs to depopulate the inverted electron QW but leaves the lower (hole) QW unaffected. Fully independent contacts are thus achieved without the need of any depletion gates, Focussed Ion Beam techniques or shadow masking during MBE growth.

The devices were grown by MBE on <100> SI GaAs substrates. Degradation of the hole gas mobility associated with diffusion of the Be dopant towards the ‘inverted’ interface was reduced by lowering the substrate temperature during the growth of the Be doped layer. A temperature of around 475°C was found to be optimal, giving an improvement in mobility of one order of magnitude over wafers grown at 550°C. The details of the observed variation of 2DHG mobility with growth temperature will be reported elsewhere.

The devices are patterned into standard Hall-bar geometries (60\(\mu\)m wide with an aspect ratio of 1:8.3, see figure 2), with six independent contacts to each layer. In regions away from the contact (the Hall bar) the InAs is completely removed with a selective etchant. (e.g. conc. HCl or Succinic Acid in Ammonia). A sufficient amount of the doped GaAs cap is also removed such that the 2DEG is confined only to a layer in an approximately triangular well over the regions of the device away from the contacts. The bandstructure of Fig.1 depicts this situation. In the simplest mode of operation, reported
FIG. 1: (Color online) (A) Schematic of the device and (B) self-consistent band structure of a typical device, away from the InAs contacts. An interlayer bias of 1.62V has been assumed.

here, a single voltage bias between any one pair of n and p type contacts, is used to induce the electrons. A threshold voltage slightly higher than the bandgap (1.52V) of GaAs is required for the onset of accumulation of electrons. Both type of contacts and carrier densities are stable and the devices show reproducible behaviour over several cooldowns from room temp to 300mK. A polyimide layer is used to protect the sidewalls of the mesa, such that the Ti/Au metallisation used to contact the InAs ohmics do not leak into the hole-layer. Bonding directly to n-type contacts is avoided to prevent possible damage to the structure. Using this procedure we have successfully produced several devices with leakage currents <100pA at interlayer bias >1.6V. The contacting scheme does not depend on the precise depth of the 2DEG/2DHG and would remain effective if the barrier separating the two layers is reduced further.

Typical Shubnikov de-Haas oscillations obtained from a device with a 15nm hole QW and 25nm barrier are shown in Fig 3. The quantum scattering times of the electrons measured from a dingle plot of the oscillation amplitudes with magnetic field (not shown) give \( \tau_q = 1-2\text{ps} \), comparable to values obtained from high mobility HEMTs grown in the same MBE chamber. The carrier density and interlayer leakage measured at several bias voltages are summarised in Fig 4. As the bias is increased, the rate of increase in carrier density, \( dN/dV \), is the same for both the electrons and the holes, within experimental errors. The mean distance (d) between the electron and hole layers can then be inferred from this capacitance (\( \kappa \varepsilon_0/d = e dN/dV \)). The observed dependence of electron density on the interlayer bias is \( N_e = 1.91 \times 10^{12} (V_{eh} - V_0) \), where \( V_0 \) is the threshold voltage and the densities are in \( \text{cm}^{-2} \). This gives a value of d=37nm, which is in agreement with the peak to peak separation of the wavefunctions obtained from the self-consistent calculations. The contact resistance of the InAs contacts was estimated from the difference between the 2-probe and 4-probe resistances. \( R_{\text{contact}} \approx 5\text{k}\Omega \) at an electron density of \( 5 \times 10^{10} \text{cm}^{-2} \) and falls to less than \( 400\Omega/\text{contact} \) at \( 2 \times 10^{11} \text{cm}^{-2} \). In the devices reported in this letter, the electron and hole densities cannot be independently controlled. As shown in Fig 4 the hole density is always higher than the electron density, because of the contribution from the Be-dopants. It is possible to incorporate a back-gate to deplete the excess hole density. This will be implemented in future devices.

Measurement of “Coulomb drag” between a 2DEG and 2DHG in closely spaced bilayers is of considerable current interest. We demonstrate that our device can be successfully used to make these measurements. A low frequency constant current is passed through one layer (the drive layer). Due to Coulomb scattering between carriers in two different layers, some momentum is transferred to the other (drag) layer. Under open circuit conditions, this leads to a voltage appearing across the drag layer. The magnitude of the voltage is a direct measure of the interlayer scattering rate. Calculations based on linearised Boltzmann transport equation give \[14, 15\]
\[
\rho_{\text{drag}} = \frac{\hbar}{e^2} \frac{2\pi e^2}{4k_B T n_1 n_2} \int \frac{dk_{\vec{k}_1}}{(2\pi)^2} \frac{dk_{\vec{k}_2}}{(2\pi)^2} \frac{dk_{\vec{k}_3}}{(2\pi)^2} \times \\
|\phi(q)|^2 q^2 f_1 f_2 (1 - f_{1'}) \left( 1 - f_{2'} \right) \delta(\epsilon_1 + \epsilon_2 - \epsilon_{1'} - \epsilon_{2'}) \quad (1)
\]

where \(\phi(q)\) is the Fourier transform of the screened Coulomb potential, the numbers denote the layer indices, the primes refer to the final states and \(f_{1,2}\) are the relevant Fermi functions. As long as the system is in the linear response regime (i.e. drive currents are sufficiently small) Onsager’s reciprocity theorem requires that the resistance measured by interchanging the current and voltage terminals should be unchanged. [17]

In the data shown (Fig 5), the error bars represent the difference obtained by interchanging the roles of the drive and drag layers. The differences are sufficiently small and \(\rho_{\text{drag}}\) increases approximately as \(T^2\). The power law can be qualitatively explained by considering the phase-space available to the initial and final states in the scattering process. The calculated magnitude of the drag resistance depends on the precise form of the interaction used. Comparison with experimentally obtained values of drag resistivity is an effective testing ground for theoretical calculations of the screened Coulomb potential. Calculations based on the Thomas-Fermi approximation in a bilayer 2D system [16,18] overestimate the screening [19] and leads to the curve shown, for comparison. This will be analysed in greater detail elsewhere.

In conclusion, we have demonstrated a novel way of fabricating an electron-hole bilayer and making independent contacts to each layer. The shallow n-type contacts do not require any annealing and the samples can be patterned into Hall-bars. Standard MBE growth and photolithographic techniques are used. Four-terminal measurements at 300mK as well as Coulomb drag experiments have been made successfully using these contacts.

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