# Direct Observation of Hole Edge Channels in a Two Dimensional Electron Gas

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We report the direct optical observation of confinement and transport of minority holes in a two dimensional electron gas. In spatially resolved magneto-optical experiments we observe hole confinement at the edge of a two dimensional electron gas and hole transport in edge channels. In a theoretical analysis we show that a repulsive edge potential for holes at the boundary of a two dimensional electron gas is caused by a polaron effect.

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Ambipolar transport has a long history in semiconductor physics. Since the Shockley-Haynes experiment [1] various groups have studied electron-hole systems and addressed different types of problems. Höpfel *et al.* [2,3] have investigated the electron-hole momentum relaxation in GaAs quantum well (QW) structures. They demonstrated negative absolute mobility of minority carriers as a consequence of electron-hole scattering, the so-called carrier drag effect. More recently, the carrier drag effect was used for direct imaging of the carrier motion in mesoscopic structures [4]. In the field of unipolar magnetotransport, the distribution of current flow in two dimensional systems is a widely studied topic. For almost ten years, the concept of edge state transport has been successfully applied in the quantum Hall regime [5]. Classically such edge states can be described as skipping orbits. They follow the boundary of a two dimensional electron gas (2DEG), which represents a potential barrier for electrons caused by depletion effects. Consequently, those diamagnetic currents have drift velocities with different signs on opposite boundaries of the 2DEG.

In our current contribution, we investigate the properties of optically excited minority holes in a 2DEG. We study the confinement and transport of these holes within the sea of two dimensional electrons in the presence of boundaries. In these studies we use spatially resolved optical techniques to image the spatial distribution of minority holes in the presence of finite electric and magnetic fields. Our experiments show for the first time that the minority holes are confined to the 2DEG by a new and unexpected edge potential. In the presence of magnetic fields, this edge potential leads to the formation of hole edge states. The underlying edge potential is shown theoretically to originate from a polaron type of attraction of the minority holes to the edge of the 2DEG.

For our experiments we use a high mobility remotely doped GaAs QW structure in order to obtain both electron and hole confinement along the growth direction. Our sample was grown on a semi-insulating GaAs substrate by molecular beam epitaxy. The layer sequence consists of a 3000 nm thick GaAs/$Al_{0.32}Ga_{0.68}As$ superlattice followed by a 15 nm thick GaAs QW, which is the active layer in our structure. After the QW, a 20 nm wide $Al_{0.32}Ga_{0.68}As$ spacer layer was grown, followed by a Si delta-doped 1.5 nm GaAs QW, a 30 nm $Al_{0.32}Ga_{0.68}As$ layer, and a 8.5 nm GaAs cap layer. The 2DEG in the 15 nm GaAs QW has a surface density of $4 \times 10^{11}$ cm$^{-2}$ and a low-field mobility of $4 \times 10^{5}$ cm$^2$/V s at $T = 700$ mK. Hall bars with a width of 10 $\mu$m have been produced by optical lithography and wet-chemical etching. The etch depth was 40 nm. The samples were mounted in a cryogenic confocal microscope setup, which is operated in a He3 system. Experiments have been performed at a base temperature of 700 mK and magnetic fields up to 3 T with a spatial resolution of 1 $\mu$m. The sample was optically excited with an Ar$^+$ laser at $\lambda = 514$ nm or a HeNe laser at $\lambda = 632.8$ nm. Detection was performed with a cooled CCD camera in the image plane of the confocal setup. Filters were introduced in front of the CCD camera to obtain photoluminescence (PL) images only in the spectral range of the 15 nm GaAs QW.

A PL image of a section of a 10 $\mu$m wide Hall bar is shown in Fig. 1(a). Optical excitation was done in this case by a defocused Ar$^+$ laser at $\lambda = 514$ nm centered in the right part of the displayed area as indicated. Clearly, the edge of the 2DEG shows an enhanced PL intensity

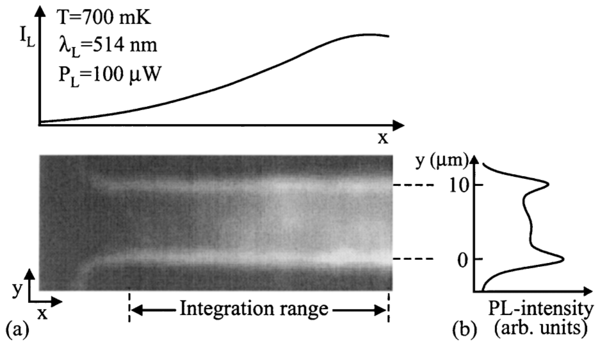

FIG. 1. (a) Low temperature PL image of the QW PL from a section of a 10 $\mu$m wide Hall bar for zero electric and magnetic field. Optical excitation is via a defocused Ar$^+$ laser with the indicated lateral intensity profile $I_L$. (b) An enhancement of the integrated PL intensity is found at both edges of the Hall bar.

compared to the inner part of the Hall bar. In the left part of the image, potential probes are visible. More quantitatively the PL-intensity enhancement at the edge of the Hall bar can be seen in Fig. 1(b), which shows a cross section of the PL intensity. The displayed PL data has been integrated over $x$ in the section between the two dashed lines indicated in Fig. 1(a). Within the given spatial resolution of 1 $\mu$m, the edge of the Hall bar shows clearly an unexpected enhancement of the PL intensity. In the mesa structure under investigation the band bending at the edges assures in a simple picture electron confinement to the Hall bar and hole repulsion from the Hall bar. Photogenerated holes would therefore be subjected to a drift field at the edge of the Hall bar which would result in hole depletion rather than enhancement.

Generally speaking, changes in the PL intensity can have different reasons, such as variations in carrier densities or in the radiative and nonradiative recombination rates. In a charged electron-hole plasma a major contribution certainly comes from the product of the local electron and hole densities. Since the electron density is decreasing towards the edges of the Hall bar, the observed PL image is consistent with an enhancement of the hole density at the edge of the Hall bar.

A proof for the existence of an additional edge potential for holes can be provided by experiments in crossed electric and magnetic fields. The general arrangement of such experiments is explained in Fig. 2(a). The boundaries of our 10 $\mu$m wide Hall bar are indicated by the dashed lines. The 2DEG in the Hall bar is subjected to a longitudinal electric field $E_X$ and a perpendicular magnetic field $B_\perp$. This, in turn, leads to the formation of a Hall field $E_{\mathrm{Hall}}$ caused by the drift motion of the 2DEG. For the magnetic fields and the sample considered in this work, $E_{\mathrm{Hall}}$ is always larger than $E_X$ ($\mu B_\perp > 1$). Electron-hole pairs are locally photocreated in the center of the Hall bar (excitation spot). Whereas the excess electrons can be neglected, the excess holes are subjected to the total electric field $E_X + E_{\mathrm{Hall}}$ and the magnetic field $B_\perp$. Consequently, the holes are expected to perform an $E \times B$ drift in the indicated direction. In the central part of the Hall bar the holes undergo therefore a drift motion which is mainly collinear with the electron motion, however, with an additional component oriented towards the lower edge of the Hall bar. If there is an effective potential barrier, which prevents holes from escaping the 2DEG, we expect the formation of skipping orbits at the edges of the Hall bar. Since the initial $E \times B$ drift is towards the lower edge of the Hall bar only the lower hole edge state will be occupied. With the given orientation of $B_\perp$ the propagation of this hole edge state will be opposite to the initial direction of hole motion.

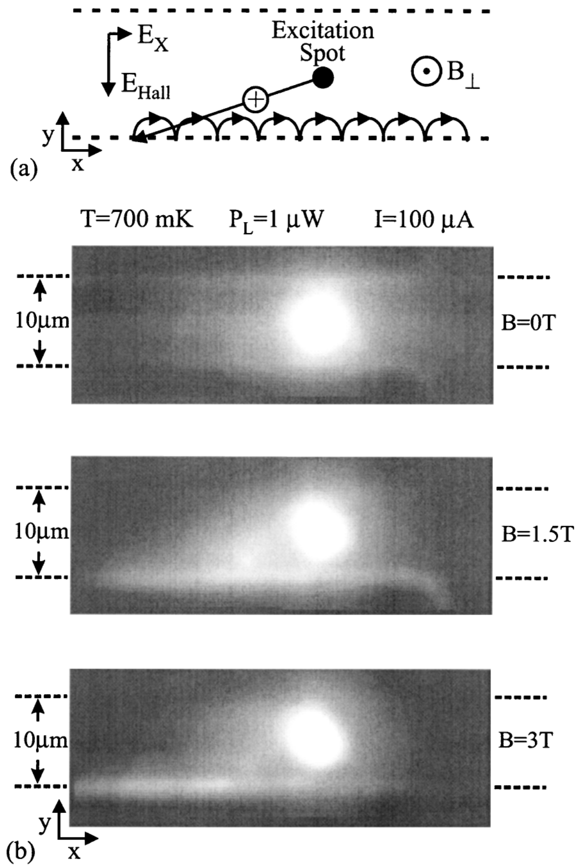

FIG. 2. (a) Schematic view of the theoretically expected hole trajectories for optical excitation in the center of the Hall bar in the presence of electric and magnetic fields. After an initial $E \times B$ drift from the excitation spot to the lower left edge of the Hall bar. For the existence of a repulsive edge potential the holes are expected to propagate in an edge state opposite to the initial direction of movement. (b) Logarithmically scaled low temperature PL images of a section of a 10 $\mu$m wide Hall bar for different magnetic fields.

Experimental data for the above-described situation is shown for different magnetic fields in Fig. 2(b). All data have been recorded for a base temperature of $T = 700$ mK, excitation with a HeNe laser at $P_L = 1$ $\mu$W, and a drift current of $I = 100$ $\mu$A. The displayed grey scale is proportional to the logarithm of the PL intensity. At $B = 0$ T, the photoexcited holes are shifted to the left, which corresponds to the electron drift direction (drag effect). Even under local excitation in the center of the Hall bar, light emission from the edge of the Hall bar seems to be slightly enhanced. At $B = 1.5$ T, the light emission is further shifted to the left and towards the lower edge of the Hall bar. The intensity from the lower edge is selectively enhanced and extends far to the right, even into one of the potential probes. While the direction of hole propagation inside the Hall bar is apparently from the excitation spot to the lower left side, the direction of propagation along the lower edge is opposite. This can be easily shown by shifting the optical excitation directly onto the lower edge of the Hall bar. Under this condition we find hole edge transport from the left to the right in agreement with the schematic picture shown in Fig. 2(a).

The situation is similar at $B = 3$ T. Because of the increased magnetic field the initial $E \times B$ drift is, however, expected to be faster by a factor of $B^2$ ($E_{\mathrm{Hall}}B$). Consequently, the occupied portion of the hole edge channel is therefore shifted further to the left. Since the hole velocity should be constant in the hole edge channel for a given edge potential and magnetic field, the space coordinate along the edge should be directly proportional to time. With an exponential decay law for holes in the edge channel, we would therefore expect an exponential decay of the QW PL along the direction of propagation at the edge. Corresponding data are shown in Fig. 3. Optical excitation is here on the upper edge of the Hall bar. As expected, only the lower edge channel is occupied by $E \times B$ drift. The observed decay of the edge PL along the positive $x$ direction in this linear scaled contour plot in fact nicely follows a single exponential law.

In the following, we discuss the origin of this effective edge potential for holes. The depletion region adjacent to the Hall bar is inaccessible to conduction band electrons but attracts positively charged holes. However, single holes in an electron gas are bound to the screening charge which they induce, an essentially polaronic effect. This binding increases with the polarizability, and, hence, the density of the electron gas. The competition between these "bare band" and polaronic effects determines the effective potential contour for holes near the edge of an electron gas.

We have calculated, within the local density approximation to density functional theory, and within the single band (for both electrons and holes), effective mass approximation, the self-consistent electronic structure for the Hall bar near the edge of the depletion region. Our model is as follows. Treating the direction of current flow $x$ as translationally invariant, we employ the nominal growth profile in the $z$ direction for the conduction band edge offset $V_B(z)$. For the shallow etched depletion region we maintain the *same growth profile* as in the 2DEG region, but we artificially terminate the positive donor layer; specifically, we take $N_d(y,z) = N_0\delta(z - z_0)\theta(-y)$, where $N_0 = 2 \times 10^{12}$ cm$^{-2}$, and $z_0$ is the position of the donor layer. The exposed GaAs surface has an interface charge [6] which can be modeled by pinning the Fermi level at 0.8 eV below the conduction band edge. The value of $N_0$ is chosen so that the 2DEG density (which, together with the surface charge, balances the donor charge) far from the edge is approximately equal to the experimental value of $4 \times 10^{11}$ cm$^{-2}$. Neumann boundary conditions for Poisson's equation are taken at large $|y|$, and at large $z$ the chemical potential is taken to be pinned in the shallow donor layer at 1 Ry* below the conduction band, i.e., we employ Dirichlet boundary conditions on the electrostatic potential, setting it to 1 Ry*.

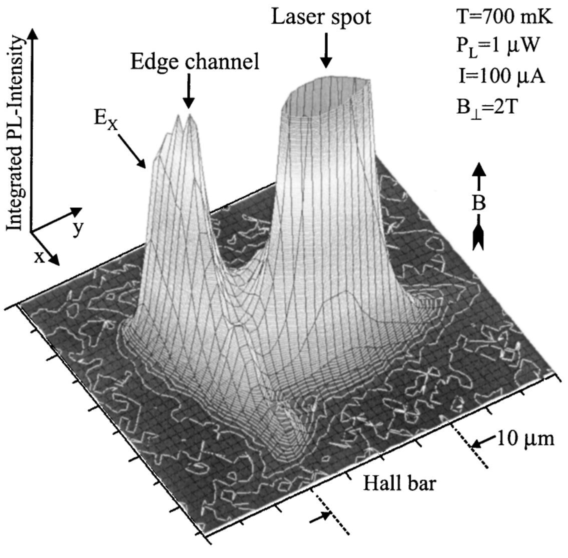

FIG. 3. Three dimensional presentation of the PL intensity for optical excitation at the right edge of the Hall bar (laser spot). By $E \times B$ drift the left edge channel is occupied. Subsequent hole propagation along the edge is in a positive $x$ direction, accompanied by an exponential decay of the edge PL intensity.

The energy of the lowest electron subband $E_0^e(y)$ is used in a 2D Thomas-Fermi approximation for the electron density [7]. The lowest hole subband $E_0^h(y)$ is calculated from the self-consistently computed electrostatic potential $\phi(y,z)$, but the charge of the hole itself is not treated self-consistently. The results (Fig. 4) show that the electron subband energy, which responds to both the electrostatic and the exchange-correlation (XC) potentials, exhibits an abrupt rise as the electron density is depleted and the XC potential disappears. Note that 2DEG depletion occurs before the edge of the donor layer (i.e., at $y < 0$) due to the electric field created by the surface charge layer. In comparison to calculations carried out in the pure Hartree approximation (not shown), the drop in electron density at the edge is more precipitous, an effect

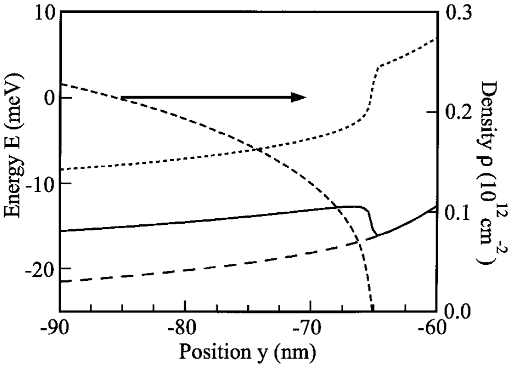

FIG. 4. Lowest conduction (dotted line) and valence (long dashed line) subband energies as a function of position. Fermi energy is energy zero, valence band shifted upward by ~1.5 eV. Valence subband with polaronic energy correction (solid line) shows that holes are repelled from the center of the Hall bar but are trapped at the edge where the electron density (short dashed line) vanishes.

which is well known in electronic structure calculations. By contrast, the hole subband energy, which is unaffected by the XC potential, decreases monotonically with $y$, suggesting that a positive test charge would escape from the 2DEG into the depletion region.

The density functional calculation for the hole subband energy does not include the polarizing effect of the hole on the electron gas. It is well known that a lowering of the hole energy is expected from its interaction with an electron gas. In Ref. [8], the authors evaluated this energy in a 3D plasmon-pole approximation, finding a correction at typical 2DEG densities to the hole subband energy for a homogeneous QW of several meV. As in that calculation, we assume a sufficiently low density of photoexcited holes, so that we can ignore interactions between holes and consider only the interaction of a single hole with the 2DEG. We evaluate this energy using a different (2D) formalism and apply the correction adiabatically to the changing density at the edge of the 2DEG.

The interaction energy between a positive point charge and a *homogeneous* 2DEG of density $n$ is

$$K(n) = -\frac{e^2}{\kappa}\int dq\left[\frac{1}{\varepsilon(q)} - 1\right], \tag{1}$$

where $\kappa$ is the background dielectric constant for GaAs ($\kappa = 12.5$). Within the static screening approximation, the $T = 0$, 2D Lindhard-Stern dielectric function is [9]

$$\varepsilon(q) = 1 + \frac{q_s}{q} \qquad q \leq 2k_F\,, \tag{2}$$

$$\varepsilon(q) = 1 + \frac{q_s}{q}\left[1 - \sqrt{1 - (2k_F/q)^2}\right] \qquad q > 2k_F\,, \tag{3}$$

where the Fermi momentum is $k_F = 2\pi\sqrt{n}$ and $q_s \equiv 2/a_0$, $a_0$ being the effective Bohr radius. Using the density $n(y)$ from the self-consistent calculation and an adiabatic approximation [i.e., $K(y) = K[n(y)]$], we thereby obtain the effective 2D hole energy corrected for the polaronic effect $E_0^h(y) + K(y)$, plotted as the solid line in Fig. 4. The sharp falloff of $n(y)$ results in a sudden vanishing of the polaronic effect at the edge of the 2DEG and a local energy "minimum" (seen in Fig. 4 as a local maximum at $y \approx -65$ nm). The corrected subband curve shows that holes generated at the Hall bar center will be drawn toward the edge but will be bound at the edge by their image charge in the 2DEG, in striking agreement with experiment. Using the pure Hartree density (not shown) gives a much shallower, nearly vanishing local minimum; hence, we may describe the hole barrier as an exchange-correlation enhanced "railing."

In conclusion, we have employed spatially resolved magneto-optical experiments to demonstrate that photoexcited minority holes created in a 2DEG are bound to the edge of that electron gas. Observation of hole edge transport in the presence of a magnetic field conclusively shows that a barrier to hole escape into the depletion region exists. A self-consistent calculation of the valence subband energy, combined with the computed polaronic contribution, produces a strong local minimum for the hole energy at the 2DEG edge.

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