Zero-resistance states induced by electromagnetic-wave excitation in GaAs/AlGaAs heterostructures

Ramesh G. Mani*†, Jürgen H. Smet†, Klaus von Klitzing†, Venkatesh Narayanamurti*‡, William B. Johnson§ & Vladimir Umansky||

* *Gordon McKay Laboratory of Applied Science, Harvard University, 9 Oxford Street, Cambridge, Massachusetts 02138, USA*
† *Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany*
‡ *Pierce Hall, Harvard University, 29 Oxford Street, Cambridge, Massachusetts 02138, USA*
§ *Laboratory for Physical Sciences, University of Maryland, College Park, Maryland 20740, USA*
|| *Braun Center for Submicron Research, Weizmann Institute, Rehovot 76100, Israel*

The observation of vanishing electrical resistance in condensed matter has led to the discovery of new phenomena such as, for example, superconductivity, where a zero-resistance state can be detected in a metal below a transition temperature T_c (ref. 1). More recently, quantum Hall effects were discovered from investigations of zero-resistance states at low temperatures and high magnetic fields in two-dimensional electron systems (2DESs)[2–4]. In quantum Hall systems and superconductors, zero-resistance states often coincide with the appearance of a gap in the energy spectrum[1,2,4]. Here we report the observation of zero-resistance states and energy gaps in a surprising setting[5]: ultrahigh-mobility GaAs/AlGaAs heterostructures that contain a 2DES exhibit vanishing diagonal resistance without Hall resistance quantization at low temperatures and low magnetic fields when the specimen is subjected to electromagnetic wave excitation. Zero-resistance-states occur about magnetic fields $B = 4/5B_f$ and $B = 4/9\,B_f$, where $B_f = 2\pi fm^*/e, m^*$ is the electron mass, e is the electron charge, and f is the electromagnetic-wave frequency. Activated transport measurements on the resistance minima also indicate an energy gap at the Fermi level[6]. The results suggest an unexpected radiation-induced, electronic-state-transition in the GaAs/AlGaAs 2DES.

Hall bars of width w, with $50 \leq w \leq 200\,\mu m$, and square-shaped specimens up to $\sim 3 \times 3\,mm^2$ were fabricated from high quality GaAs/AlGaAs heterostructures exhibiting an electron density $n(4.2\,K) \approx 3 \times 10^{11}\,cm^{-2}$ and a mobility $\mu(1.5\,K) \approx 1.5 \times 10^7\,cm^2\,V^{-1}\,S^{-1}$. Typically, a specimen including either Au/Ge-Ni or In contacts was mounted inside a waveguide, immersed in pumped liquid helium, and irradiated with electromagnetic waves (microwaves) over the frequency range $27 \leq f \leq 115\,GHz$, at an estimated power level of $\leq 1\,mW$, over a cross-sectional area of $\leq 135\,mm^2$ in the vicinity of the sample. The range of f was spanned piecewise using an array of sources. The current axis in the specimen was oriented either parallel or perpendicular to the electromagnetic-wave polarization axis of the waveguide. Observed experimental features appeared to be insensitive to the type of contacts, the shape of the sample, the current orientation with respect to the polarization axis, and the magnitude of the current. Conversely, these physical phenomena were quite sensitive to the temperature, the microwave frequency, and the radiation power. The systematic dependence upon these latter variables served to rule out spurious effects.

Figure 1a shows the diagonal (R_{xx}) and Hall (R_{xy}) resistances, which were measured in the four-terminal configuration, using standard low-frequency a.c. lock-in techniques. Notably, R_{xx} and R_{xy} exhibit the usual quantum Hall behaviour for $B \geq 0.4\,T$ at $f =$ 103.5 GHz (refs 2–4). In contrast, at $B < 0.4\,T$ (Fig. 1a inset), a radiation-induced signal occurs and, remarkably, the resistance vanishes over a broad interval of B around $B = 0.198\,T$. Here, the scale factor to convert R_{xx} to the resistivity ρ_{xx} is 1.

Further high-resolution measurements are shown in Fig. 1b. Without electromagnetic excitation, R_{xx} exhibits Shubnikov–deHaas oscillations for $|B| \geq 0.2\,T$. Radiation induces additional oscillations, which might be attributed to scattering between Landau levels[7], as in the magneto-phonon effect[8]. Yet, the data reveal that, at the minima, R_{xx} falls well below the resistance measured without radiation and it vanishes around magnetic fields of $4/5\,B_f$ and $4/9\,B_f$, set by $B_f = 2\pi fm^*/e$ with $m^* = 0.067m$, the GaAs electron effective mass[9]. Although these zero-resistance states exhibit a flat bottom as in the quantum Hall regime[2], R_{xy} does not exhibit plateaus over the same B interval. A normalized B^{-1} plot (Fig. 1c) demonstrates periodicity in B^{-1} with minima that satisfy $B_{min}^{-1}/\delta = [4/(4j+1)]^{-1}$ with $j = 1, 2, 3\ldots$ Here, δ is the oscillatory period in B^{-1}, which agrees with B_f^{-1} within experimental uncertainties ($\sim$1%). Notably, half-cycle plots also confirmed a '1/4-cycle phase shift' of the extrema with respect to integral B_f^{-1}, which is indicated by Fig. 1c.

Figure 2 shows the f dependence of the R_{xx} oscillations. For f up to 40 GHz (not shown), R_{xx} exhibited just a minimum at $4/5\,B_f$. A data-fit with exponentially damped sinusoids[10] suggested that the resistance-oscillation frequency F increases linearly with f, and that the oscillation amplitude decay in B^{-1} is characterized by an f-independent damping parameter. An evaluation of m^* using $dF/df = 2\pi m^*/e$ yielded $m^*/m = 0.067$, consistent with expectations for GaAs (refs 9, 11, 12). Over the intermediate f range (Fig. 2a), a zero-resistance state is first observed at $4/5\,B_f$; this shifts to higher B with increasing f. Similar behaviour continues onto the

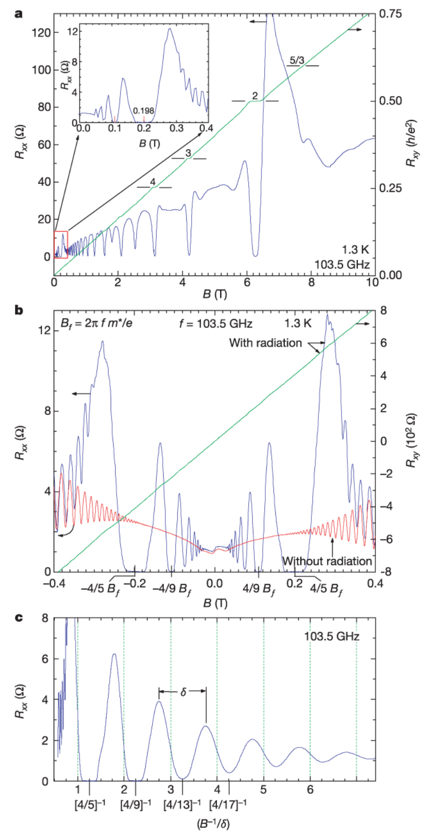

Figure 1 The Hall effect and the magnetoresistance in a high-mobility 2DES, with and without electromagnetic-wave excitation. **a**, The Hall (R_{xy}) and diagonal (R_{xx}) resistances in a GaAs/AlGaAs heterostructure under excitation at 103.5 GHz. Quantum Hall effects occur at high B as $R_{xx} \rightarrow 0$. Inset, an expanded view of the low-B data showing $R_{xx} \rightarrow 0$ in the vicinity of 0.198 T. **b**, Data over low magnetic fields obtained both with (w/) and without (w/o) radiation at 103.5 GHz. Note the vanishing resistance under radiation in the vicinity of $\pm 4/5\,B_f$ and $\pm 4/9\,B_f$, and the linear Hall effect over corresponding B intervals. In contrast, quantum Hall systems typically exhibit plateaus in the Hall resistance over the B intervals where vanishing resistance is observed. **c**, A normalized B^{-1} plot of the low-B data. Resistance minima occur at $[4/(4j+1)]^{-1}$ with $j = 1,2,3\ldots$ Here, δ is the oscillatory period in B^{-1}, which agrees with B_f^{-1} within experimental uncertainties ($\sim$1%). Note that the $j = 1$ and $j = 2$ states exhibit vanishing resistance.

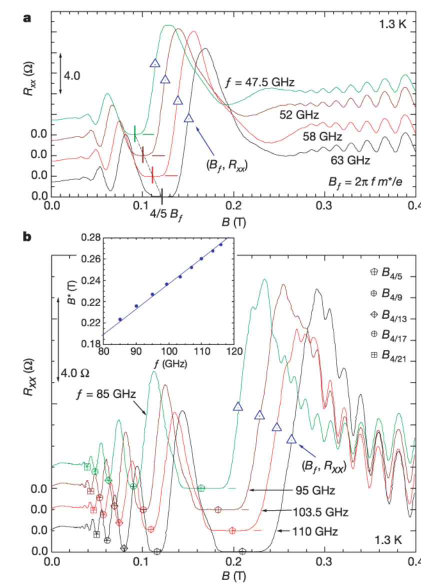

Figure 2 The development of the radiation-induced zero-resistance states with the electromagnetic-wave frequency, f. **a**, Over the intermediate f-range, a zero-resistance state occurs at $4/5\,B_f$. The triangles mark R_{xx} at the magnetic field $B_f = 2\pi fm^*/e$, where the oscillatory curves exhibit neither a maximum nor a minimum. **b**, Over the highest f-range, a zero-resistance state is seen at both $4/5\,B_f$ and $4/9\,B_f$, marked here as $B_{4/5}$ and $B_{4/9}$. Inset, B^* calculated using the (weighted) first five resistance minima as a function of f. We find: $dB^*/df = 2.37\,mT\,GHz^{-1}$, where $B^* = \sum_{j=1}^{5}\{[4j+1)/4]B_{4/(4j+1)}\}/5$.

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highest f range (Fig. 2b), except that a second zero-resistance state becomes evident around $B = 4/9\,B_f$. Here, the sample quality seems to set the lowest magnetic field at which these oscillations can be observed.

Power-dependence data (Fig. 3a) indicate that as the radiation intensity is increased (that is, as the attenuation factor in decibels (dB) $\rightarrow 0$), the resistance at $B = [4/(4j+1)]B_f$ tends to decrease and, about $4/5\,B_f$ and $4/9\,B_f$, $R_{xx} \rightarrow 0$. The current dependence data shown in Fig. 3b demonstrate insensitivity to the current and the Hall electric field. The temperature (T) variation of R_{xx} at 85 GHz (Fig. 3c) displays both the strong T-dependence of R_{xx} and the low-T requirement for the zero-resistance state. The T-variation of R_{xx} at the deepest minima suggests activated transport; that is, $R_{xx} \propto \exp(-\kappa/2k_BT)$, where k_B is Boltzmann's constant and κ is the activation energy (refs 2, 6; Fig. 3d).

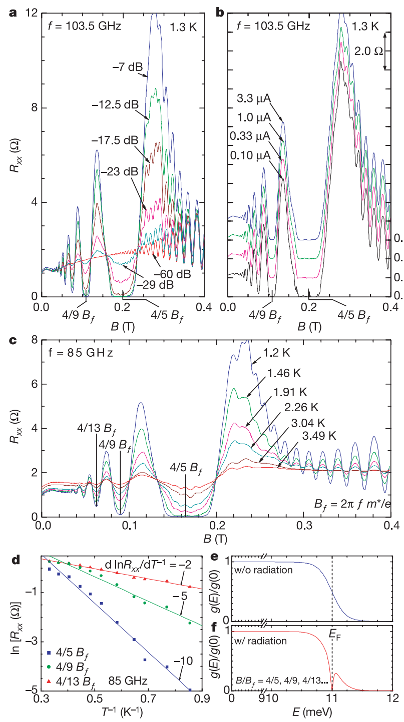

Figure 3 The dependence of the magnetoresistance upon the radiation power, current and the temperature. **a**, The amplitude of the radiation-induced resistance oscillations increases with increasing power, that is, attenuation $\rightarrow$ 0 dB, as the resistance at the minima fall below R_{xx} without radiation, leading to zero-resistance states at $4/5\,B_f$ and $4/9\,B_f$. The radiation power level is estimated to be $\leq$1 mW. **b**, The lineshape of the radiation-induced resistance oscillations is insensitive to the magnitude of the current. **c**, The T-dependence of the magnetoresistance at 85 GHz under constant-power excitation. The radiation-induced resistance minima become deeper at lower temperatures. Note that additional, reproducible, weak resistance oscillations occur about the $4/5\,B_f$ minimum at higher temperatures. **d**, The natural logarithm of the resistance versus the inverse temperature, at $B = 4/5\,B_f$, $4/9\,B_f$ and $4/13\,B_f$, for the 85-GHz data of **c** suggests activated transport and gap formation. Here, $\kappa/2k_B \approx 10$ K for the $4/5\,B_f$ state at 85 GHz. **e**, A sketch of the normalized density of states versus the energy in the absence of radiation at low B, when Landau level quantization is imperceptible. **f**, A sketch of the effective density of states versus E about $B = [4/(4j+1)]B_f$, with $j = 1,2\ldots$ when radiation induces a zero-resistance state. The formation of an energy gap around E_F is suggested by observed activated transport (see **d**).

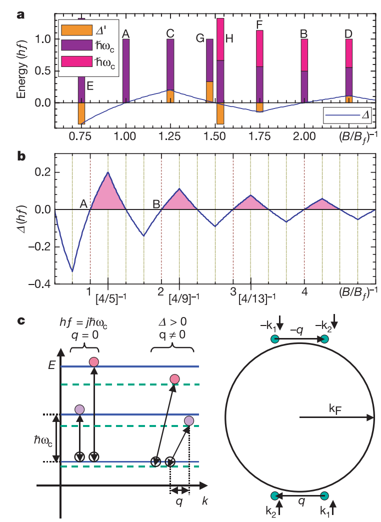

Figure 4 Energy commensurability, inter-Landau-level electron–hole excitations, and the pairing conjecture. **a**, Energy commensurability between the photon energy, hf, and the Landau level spacing, $\hbar\omega_c$, as a function of the normalized inverse field, $(B/B_f)^{-1}$. At $(B/B_f)^{-1}$ marked by A and B, the photon energy hf spans $\hbar\omega_c$ and $2\hbar\omega_c$, respectively, and the energy difference Δ' vanishes, that is, $\Delta' = hf - j\hbar\omega_c = 0$. Small deviations from $(B/B_f)^{-1} = 1$ and $(B/B_f)^{-1} = 2$ lead to deviations from $\Delta' = 0$, as $\hbar\omega_c$ changes with the magnetic field. Thus, at C and D, Δ' becomes positive, and at E and F, Δ' takes on negative values. At $(B/B_f)^{-1} = 3/2$, both $(B/B_f)^{-1} = 1$ and $(B/B_f)^{-1} = 2$ are equidistant in the B^{-1} plot; following the branches from $(B/B_f)^{-1} = 1$ and $(B/B_f)^{-1} = 2$ to $(B/B_f)^{-1} = 3/2$ would yield a double valued Δ', which is shown as G and H. The B^{-1} periodicity observed in the physical effect, and the symmetry at $(B/B_f)^{-1} = 3/2$, suggest therefore that the physical energy surplus/deficit Δ ought to vanish at $(B/B_f)^{-1} = 3/2$. The full construction of Δ from Δ' follows this notion. **b**, The periodic variation of Δ, the energy surplus/deficit relative to direct inter-Landau-level excitations, is plotted versus $(B/B_f)^{-1}$. The coloured regions represent $(B/B_f)^{-1}$ intervals where Δ is positive. Experimental results (Fig. 1c) indicate that radiation-induced zero-resistance-states occur about such $(B/B_f)^{-1}$ intervals. **c**, Left: at $hf = j\hbar\omega_c$, electromagnetic-radiation-induced e–h excitations (excitons) across an integer number of Landau levels do not carry any wavevector, that is, $q = 0$. On the other hand, when $\Delta > 0$, excitons can realize a surplus energy, which can help to access the finite wavevector portion of the excitonic dispersion relation. Right; the Fermi surface in the investigated regime. Under electromagnetic-wave excitation, these specimens can include a steady-state population of e–h excitations (excitons) and a high-mobility two-dimensional 'metal' in a coplanar geometry. q-carrying excitons are proposed to bring about an electron pairing instability by exciton exchange[23–27], resulting in a spectral gap. The periodic reappearance of q-carrying excitons leads to the periodic reappearance of such a spectral gap and vanishing resistance.

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Relevant scales include the cyclotron energy, $\hbar\omega_c$, the photon energy, hf, and the Landau level broadening $\pi k_B T_D$ (here T_D is the Dingle temperature). At the $B = 0.198$ T minimum (Fig. 1a), $\hbar\omega_c = 0.342$ meV is 4/5 of $hf = 0.428$ meV at 103.5 GHz, and the Hall effect implies a filling factor of ~63. The transport mean free path is 138 μm for $\mu = 1.5 \times 10^7\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$. The transport lifetime, $\tau_t = m^*\mu/e = 5.8 \times 10^{-10}$ s, and the single particle lifetime $\tau_S = \hbar/2\pi k_B T_D = 1.1 \times 10^{-11}$ s, suggest a large ratio, $\tau_t/\tau_S \approx 53$, indicative of mostly small angle scattering[4,10]. The predominance of small angle scattering, and a 7–10 times higher sample mobility, differentiates our specimens from the samples examined in ref. 7. We attribute the occurrence of zero-resistance states in our study, and the lack of them in ref. 7, to these differences. Notably, level broadening determined from T_D suggests that the density of states at low B looks approximately like that at $B = 0$ (Fig. 3e).

In translationally invariant systems, cyclotron resonance is independent of electron–electron interactions and consists of a resonance at $hf = \hbar\omega_c$ only[13]. Our samples include impurity scattering, surface roughness, and a Hall electric field, which could make possible transitions at $hf = j\hbar\omega_c$ (refs 14, 15). In a bounded specimen, the collective plasma mode can also hybridize with cyclotron resonance, yielding magnetoplasmons at $B > 0$ (refs 16, 17). A search for plasma frequency, ω_p (ref. 16), sensitivity produced a null result[5,19]. In addition, R_{xx} under radiation does not directly manifest the bare cyclotron resonance ($\hbar\omega_c$), or its harmonics ($j\hbar\omega_c$), as evidenced by the phase shift of the extrema with respect to integral B_f^{-1} in a B^{-1} plot. Thus, there is no obvious violation of Kohn's theorem[13].

The sample mobility ($\mu \geq 10^7\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$) implies that $\mu B > 1$ for $B \geq 1$ mT. Thus, where R_{xx} vanishes, the Hall angle is ~90°, implying electron transport along equipotentials[2,4]. In this limit, back scattering at the Fermi surface yields a finite R_{xx}. The radiation-induced vanishing-resistance thus indicates that scattering is prohibited, while the activated resistance indicates that gap formation (Fig. 3f) suppresses scattering.

A full theory of this phenomenon, which considers the interaction of electrons with the electromagnetic field, awaits development. Meanwhile, we suggest an approach that relates a spectral gap to the presence of radiation-induced excitons, via an excitonic mechanism for electron pairing: in this 2DES, excitonic electron–hole (e–h) excitations between Landau levels near the Fermi level can be produced by photons, upon conserving energy and wavevector, when hf approaches $j\hbar\omega_c$ (refs 20–22). Further, a steady-state population of excitons can occur under constant radiation. Thus, these specimens could include electrons and excitons in a coplanar geometry, resembling proposals where a weak attractive interaction between electrons can occur by exciton exchange[23–27]. Unlike some considered systems[23–26], this 2DES includes low-energy excitons which implies gap formation at low ($\sim\hbar\omega_c/k_B$) temperatures[24]. Yet, the periodicity and phase of the zero-resistance states, the role of B_f, and the power dependence can be qualitatively understood within such an approach, after accounting for Landau quantization.

According to theory, excitons in the 2DES follow the energy dispersion relation $E^j_\mu = j\hbar\omega_c + \Delta E^j_\mu(q)$ and include a wavevector q-dependent energy shift of order $e^2/\varepsilon l_0$, where l_0 is the magnetic length[21,22]. Thus, a necessary component for exciton-mediated electron pairing, finite-q excitons[25], might be accessible to the system when electron–hole excitations obtain a surplus energy ΔE^j_μ. We examine the interplay between the fixed hf and the B-tunable $\hbar\omega_C$ (Fig. 4a) in order to identify the regime where a surplus energy might occur. In this figure, at A and B, an integer number of Landau levels are commensurate with hf, and the energy difference vanishes, $\Delta' = hf - j\hbar\omega_c = 0$, indicating the absence of an energy surplus or deficit. Also, small excursions from $(B/B_f)^{-1} = 1$ (or 2) lead to deviations from $\Delta' = 0$. Following the branches from $(B/B_f)^{-1} = 1$ and $(B/B_f)^{-1} = 2$ yields a double valued Δ' at $(B/B_f)^{-1} = 3/2$. The B^{-1} periodicity observed in the resistance, and the symmetry at $(B/B_f)^{-1} = 3/2$, suggest that the physical energy surplus/deficit, Δ, ought to vanish at $(B/B_f)^{-1} = 3/2$ in this situation. The construction of Δ from Δ' (Fig. 4b) follows this notion. Then, Fig. 4b indicates that Δ takes on maximal positive values at $(B/B_f)^{-1} = [4/(4j+1)]^{-1}$, favouring finite-$q$ excitons over the interval $[4/4j]^{-1} < (B/B_f)^{-1} < [4/(4j+2)]^{-1}$. The data (Fig. 1c) indicate that radiation reduces R_{xx} over corresponding intervals.

When $\Delta > 0$, electron pairing by exciton exchange can occur as in Fig. 4c (ref. 25). Here, the scattering of an electron from $\mathbf{k}_1$ to $\mathbf{k}_2 = \mathbf{k}_1 + \mathbf{q}$ provides wavevector for the exciton, and facilitates access to the finite-q portion of the dispersion relation. Such correlated scattering could produce a pairing instability near the Fermi surface[23–27], resulting in a spectral gap. As radiation facilitates q-carrying excitons, a spectral gap can occur only under illumination. The periodic (in B^{-1}) reappearance of q-carrying excitons leads to the periodic reoccurrence of electron pairing, and vanishing resistance. In contrast, when $\Delta < 0$, a local energy deficit for exciton creation increases the electron inelastic-scattering cross-section, producing radiation-enhanced resistance over corresponding intervals. Thus, this interpretation suggests that excitons induce a pairing instability[23–26] in the 2DES system around $B = [4/(4j+1)]B_f$, which leads to a spectral gap, activated transport[6] and zero-resistance-states[3], while the lack of phase coherence prevents the realization of typical superconductivity[1,28]. These results complement studies of exciton condensation in the quantum Hall regime[29,30], and studies of exciton ordering and transport in coupled quantum wells[31,32]. □

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Correspondence and requests for materials should be addressed to R.G.M. (e-mail: mani@deas.harvard.edu).