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Invited

Classical Ballistic Electron Optics in Two Dimensions

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We demonstrate that two-dimensional ballistic electrons in ultra-high mobility GaAs-AlGaAs heterostructures can be controlled in ways analogous to the manipulation of photons in optical systems. Among the "electron-optical" structures we demonstrate are emitters, detectors, reflectors, absorbers, and refracters. These advances may enable the design of new types of electronic circuits.

Using sophisticated lithographic patterning techniques, modulation doped GaAs-(AlGa)As heterostructures, providing high quality two-dimensional electron systems (2DES) can be structured to dimensions which allow the observation of lateral quantum confinement.[1] Recently electron mobilities beyond $10^7 cm^2/Vs$[2] have been realized in GaAs-AlGaAs heterostructures corresponding to elastic mean free paths of nearly 100μm. Since this considerably exceeds the characteristic electron wavelength, analogies between ballistic electron propagation and geometrical optics come to mind. Towards this goal we develop various "optical" techniques to control ballistic electrons.

The samples described here are all modulation doped GaAs-(AlGa)As heterostructures with the distance between the surface and 2DES ≈0.5μm. Diffused Ni/Au/Ge layers are used as ohmic contacts and gates are evaporated Ti/Au. Both contacts and gates are photolithographically defined. All experiments are performed at temperature =0.3K after illuminating the samples at ≈2K.

The magnetic focusing (MF) technique[3] is used to directly measure the ballistic mean free path.[4] Electrons are injected by a point contact (emitter) and refocused by a perpendicular magnetic field onto a second point contact (collector). The injected electrons are specularly reflected from the boundary between the emitter and collector. The magnetic field B refocuses the injected electrons onto the collector whenever the emitter-collector distance d is an integer multiple of the cyclotron orbit diameter $d_{cyc}=2\hbar k_F/eB$ (k_F is the Fermi wave vector). This results in the collector voltage having a periodic dependence in B with period $2\hbar k_F/ed$, where d is the distance between the emitter and collector.

Fig. 1 shows the relative collected current I_c/I_e as a function of d on a semi-logarithmic plot. The line is a least square fit to an exponential of the form $e^{-d/\lambda}$ with λ=10μm. The data fit extremely well to such an exponential dependence over almost three orders of magnitude. Since the electrons typically follow semicircular paths we define the ballistic mean free path to be $\lambda_b=(\pi/2)\lambda=15\mu m$. In this sample the elastic mean free path, as deduced from the mobility $\mu=5.5\times10^6 cm^2/Vs$ and electron density $n=1.1\times10^{11} cm^{-2}$, is $\lambda_\mu=28\mu m$. Thus $\lambda_\mu/\lambda_b\approx2$. It is not unreasonable that λ_b is less than λ_μ because λ_μ is the path length after which an electron has lost all its momentum in the direction of its original trajectory. This may require as few as one large angle scattering event or many small angle scattering events. In the MF experiment on the other hand small angle scattering events may be weighed more strongly than in mobility measurements.

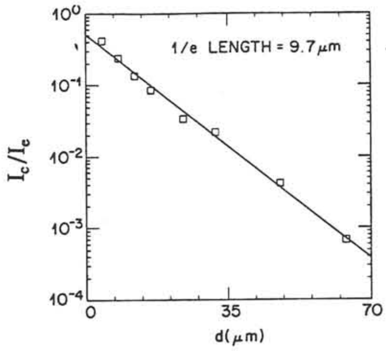

Fig. 1. Amplitudes of the MF oscillations vs emitter-collector distance d.

MF oscillations are also seen in a much simpler geometry (not shown). The sample consists of 5μm wide ohmic contacts, diffused into the mesa edge, and separated by 30μm. Ballistic electrons are injected by one ohmic contact and detected by a second one. MF oscillations are observed with each peak being comparable in amplitude, indicating that the depletion region from the mesa edge specularly reflects electrons as well as the depletion region from a gate. Secondly, this data shows that simple ohmic contacts can be used as point sources and detectors in place of split gate point contacts, which can simplify the fabrication steps and allow for internal (off the edge) electron emitters and/or detectors.

Since depletion regions from mesa edges and gates effectively act as "shiny" surfaces, it would be very useful to have the analog of "black paint". Towards this goal we demonstrate electron absorbers.[5] The inset of Fig. 2 is a photograph of the sample used to demonstrate the absorber. The surface gates are labeled 1-5 and ohmic contacts are labeled A-F. The gates are biased to form point contacts associated with ohmic contacts A, B, and D. MF measurements are separately performed from point contacts A to B and from B to D (dashed lines). A and B are separated by the depletion region created by gate 2, while B and D

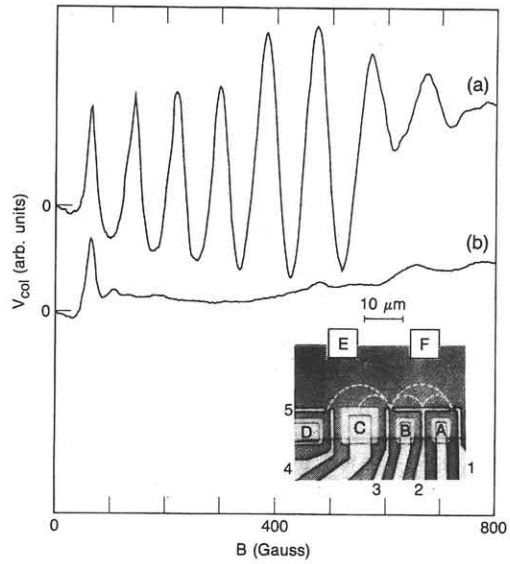

Fig. 2. Inset: geometry used to demonstrate absorber. (a) MF trace from A-B separated by depletion region from gate 2. (b) MF trace from B-D separated by ohmic contact C.

are separated by diffused ohmic contact C. The A-B MF trace (Fig. 2(a)) shows many focusing peaks as usual. However the B-D MF trace (Fig. 2(b)) shows only the first peak. All the peaks requiring one or more reflections are gone. This demonstrates that ohmic contact material either reflects the carriers in random directions or relaxes their energy to E_F. The MF technique does not distinguish between both processes, but in any case the ohmic contact material destroys the specular reflectivity and can be employed as the analog of black paint in photon optics.

An abrupt variation of the electron wavelength at an interface between two 2D systems of different densities leads to a refraction of the electron path. Surface gates can be utilized to locally vary the electron density and create refractive components. However, in order to utilize them, it is important to understand the ballistic propagation under such gated regions. The inset of Fig. 3 shows the sample used to investigate this.[5] Ohmic contacts are labeled G-J whereas the gates are labeled 6-10. Contacts G and H have associated point contacts.

MF experiments are performed between G and H with the electrons (dashed lines) specularly reflecting from the mesa edge, which cuts in between the two point contacts. The electron density between G and H is adjusted by applying a bias V_8 to gate 8, which covers a $40\times20\mu m^2$ area. MF measurements are performed at various values of V_8. The period of the MF oscillations determines k_F which in turn determines the density $n(V_8)$. The amplitude of the MF oscillations is a measure of the fraction of electrons which make it to the collector unscattered. These results are shown quantitatively in Fig. 3. The dashed line labeled n_o in Fig. 3 indicates the density outside the gated region after illumination. The important point to derive from Fig. 3 is that when $n(V_8)\approx n_o/2$ nearly all the ballistic electrons are scattered before reaching the collector. This may either be due to reduced screening at lower electron densities or increased inhomogeneities created by the biased gate. In any case when designing refractive structures, one should keep this result in mind.

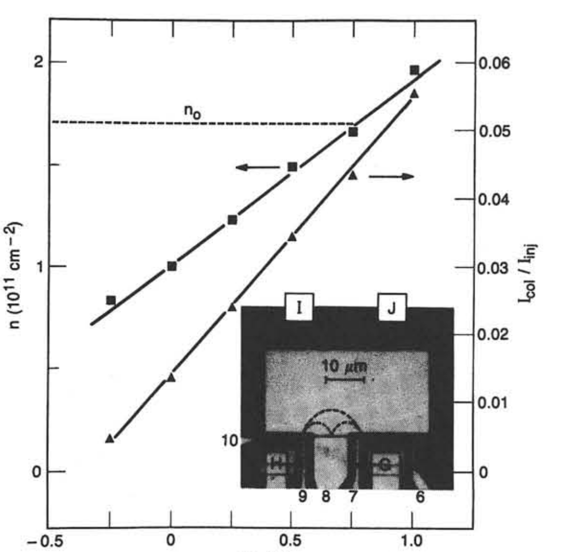

Fig. 3. Inset: geometry used to investigate ballistic propagation vs density. Squares: density vs gate voltage V_8. Triangles: relative collected current vs V_8.

Fig. 4 is a photograph of the first structure used to demonstrate refraction of ballistic electrons[6]. Subsequently there have been additional reports of electron refraction.[7,8] The gates are labeled 1-5 and the ohmic contacts are A-F. Gates 4-5 and 1-2 form point contacts labeled e and d respectively. Gate 3 is the refractive structure in the shape of a lens. The refraction of ballistic electrons at a potential step is shown in the inset of Fig. 4 for density $n>n'$. As electrons traverse from left to right they lose kinetic energy. Since the component of momentum parallel to the interface is conserved, it can be shown [6] that for electrons propagating in the vicinity of the Fermi surface $\sin\theta/\sin\theta'=(n'/n)^{1/2}$. Thus the relative index of refraction $= (n'/n)^{1/2}$. Before attempting the electrostatic electron focusing in this configuration, the density outside the lens n and the dependence of the density under the lens $n'(V_3)$ are measured using Shubnikov-deHaas techniques.

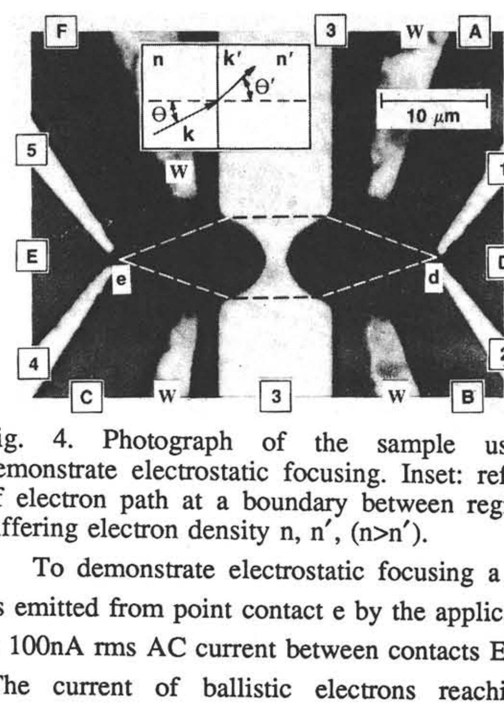

Fig. 4. Photograph of the sample used to demonstrate electrostatic focusing. Inset: refraction of electron path at a boundary between regions of differing electron density n, n', (n>n').

To demonstrate electrostatic focusing a current is emitted from point contact e by the application of a 100nA rms AC current between contacts E and C. The current of ballistic electrons reaching the detector point contact d (a distance 32µm from e) is monitored by measuring the voltage build up between contacts D and B. The solid trace in Fig. 5(a) shows the relative detected current vs. V_3. The top scale is the relative index of refraction as determined above. At $n'=0$ the electrons emitted from e are completely reflected from the lens and no ballistic electrons make it to d. As n' increases ballistic electrons begin to pass below the lens but are strongly refracted to a focus between the lens and d. As n' increases further the focus moves through d, at which point a peak in detected current

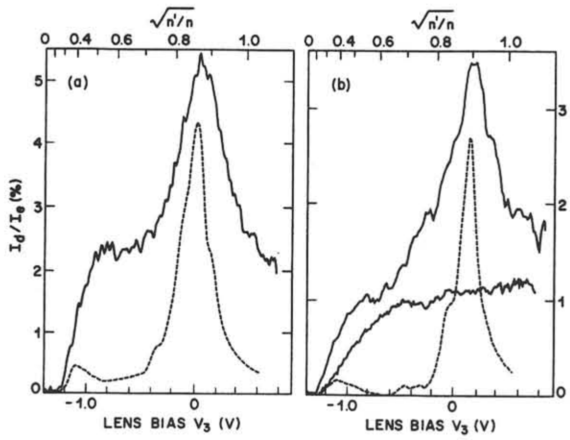

Fig. 5. Lens focusing data (upper solid traces) and theory (dashed traces) for two different lenses (a) and (b). Lower solid trace in (b): lens focusing data after deposition of a 10μm wide stripe of gate metal over the lens.

I_d is seen at $(n'/n)^{1/2}$=0.87. For larger values of n' the focal point moves behind d leading to a renewed drop in I_d. At n'=n all electrons pass the lens unrefracted. The upper solid trace in Fig 5(b) is similar data for a different lens with an emitter-detector distance of 42μm. After performing the focusing measurements a 10μm wide stripe of gate metal is deposited over the lens to drastically alter its shape, and the focusing experiment is redone (lower solid trace in Fig. 5(b)). This time the focusing peak is gone, indicating that the focusing peak is indeed due to the curvature of the lens. The dashed lines in Fig. 5 are the results of ray-tracing computer simulations. The exact shapes of the lenses are taken from scanning electron microscope photographs of the lenses. The positions of the peaks agree extremely well with the data. The widths are somewhat narrower than the data, presumably due to scattering, which is not included in the simulations.

Fig. 6 is a photograph of a second type of refractive structure, a prism.[8] Gates are labeled 1-9, ohmic contacts A-H, absorbers W, injecter point contact f, and collector point contacts a,b,c. The prism (gate 5) is demonstrated to refract a beam of ballistic electrons (dashed lines) between collectors a,b, and c.

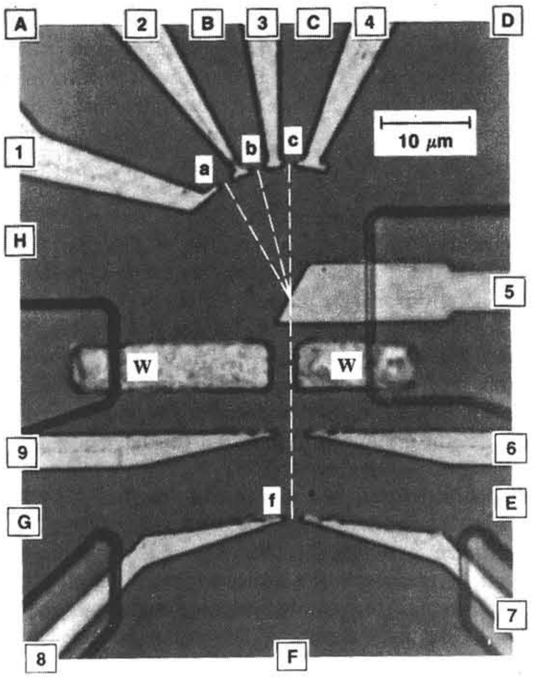

Fig. 6. Photograph of the sample used to demonstrate refractive switching. Dashed lines indicate electron paths for three prism voltages V_5.

In conclusion we demonstrate that ballistic electrons in high quality 2D systems can be manipulated in ways very similar to photons in optical systems.

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