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High-frequency conductivity of ion-beam-defined quantum wires with a self-aligned gate

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Abstract. Quasi one-dimensional quantum wire arrays are fabricated by low-energy ion beam exposure of AlGaAs–GaAs heterostructures containing a high-mobility two-dimensional electron system (2DES). The mask used for the ion beam exposure consists of a metal grating evaporated on the crystal surface, which also serves as a gate after irradiation. This self-aligned gate allows us to change the electron density in the wires without changing the electronic wire width. The linewidths of the dimensional resonances in the far infrared (FIR) of these wire arrays confirm this assertion. The FIR transmission spectra are compared with previous results obtained using wire arrays that were density tuned with a distance-modulated gate. Furthermore, a higher-order resonance is observable, indicating that the confinement potential has non-parabolic contributions.

1. Introduction

At present much interest is being devoted to the electronic properties of one-dimensional (1D) electron systems. Different methods have been developed to fabricate 1D electron wires out of the two-dimensional electron system at the interface of an AlGaAs–GaAs heterojunction [1]. Among other techniques low-energy ion beam exposure is used to deplete the electron system from unmasked areas [2–6]. This technique has some intriguing properties: the sample surface remains nearly unaffected during the patterning process [6], the mask is transferred very accurately to the electron system [4, 6], and the potential boundaries are found to be very rough in comparison with quantum wires patterned by other methods [3, 6]. The latter two properties are a consequence of the small lateral depletion widths associated with the ion beam exposure technique. From the small depletion widths it has been inferred that the form of the confinement potential is rather steep. In [6] the properties of the collective high-frequency excitations in ion beam defined 1D wires have already been investigated. There it was found that the rough wire boundaries dominantly influence the linewidth of the so-called dimensional resonance at small magnetic fields where the electrons collectively move perpendicular to the wire boundaries. A distance-modulated gate was employed, which acted in essence like a split gate with field electrodes on either side of the ion-beam-defined electron wire. It was found that the linewidth narrows considerably, if the wires were electrostatically squeezed to smaller widths, so that the boundaries were removed from the exposed areas. Using a distance modulated gate both the wire width and electron density in the wires were tuned simultaneously [6]. Here we present results obtained on wire arrays defined with a self-aligned gate, in which it may be expected [7] that the electron density is controlled by the gate voltage without significant change of the wire width. This assertion is verified by the behaviour of the resonance linewidths. Furthermore, here the large signal-to-noise ratio of our data allows us to resolve a higher-order dimensional resonance, indicating that non-parabolicity of the confinement potential in ion-beam-defined 1D wires is important.

2. Experimental notes

Our electron wires are prepared from a high-mobility AlGaAs–GaAs heterostructure material grown by molecular beam epitaxy. The two-dimensional electron system (2DES) is located 60 nm below the crystal surface at the interface between the GaAs layer and a 15 nm thick $Al_xGa_{1-x}As$ spacer layer ($x = 0.3$). On top of this a Si δ-doped sheet (3.9×10^{16} m^{-2}) is grown, followed by

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a superlattice consisting of 5 nm $Al_xGa_{1-x}As$ and nine periods of alternating GaAs (2 nm) and AlAs (2 nm) and a cap of 4 nm GaAs. The two-dimensional electron density determined from Shubnikov–de Haas measurements on macroscopic Hall-bar devices is found to be 5×10^{15} m^{-2} with a mobility of 40 m^2 V^{-1} s^{-1} at a temperature of $T = 4.2$ K.

Figure 1 shows a schematic view of the sample surface after processing. The irradiation mask prepared on top of the crystal surface consists of a 6 nm thick semitransparent NiCr grating with a period of 480 nm. The metal grating is fabricated by lift-off of a metal layer evaporated on a holographically defined photoresist grating. The metal stripe width is 300±30 nm. The wire array covers an area of about (2 mm)^2 in order to get a sufficient signal-to-noise ratio in the FIR transmission measurements. This grating gate is prepared on top of a large-period (100 μm) NiCr grating consisting of 2 μm wide stripes oriented perpendicular to the stripes of the short-period grating. The large-period grating ensures that a small number of defects in the wire array cannot inhibit the charge density tunability of the whole array. The gate voltage is applied with respect to the patterned electron system itself. Before ion beam exposure an ohmic contact is established to the two-dimensional electron system via an alloyed AuGe–Ni contact. To prevent isolation of this contact from the patterned electron system during irradiation, a photoresist mask is prepared to define a conducting bridge between the individual wires and the alloyed contact.

Irradiation with Ne ions accelerated by a 300 V potential ramp depletes mobile electrons from the unmasked area. With the metal grating used as an irradiation mask the gate inherently is located above the patterned electron system ('self-aligned gate'). In contrast to other preparation techniques, as for example distance-modulated gates [8] or etching [9], the self-aligned gate configuration enables us to field-effect tune the electron density without changing the wire width [7]. Details concerning the ion beam patterning technique can be found in [6]. The applied ion dose is approximately 3 mC cm^{-2}, a value found to be sufficient to deplete the mobile electrons from the unmasked areas [6]. The patterning by low-energy ion beam exposure has been shown to create structures with very small depletion lengths [4, 6], i.e. the actual difference of the mask width and the electronic wire width is less than 40 nm [6]. This value is much smaller than in etched or in field-effect-patterned quantum wires. Material removal during the irradiation is found to be in the range of only 2–3 nm and the boundaries between irradiated and non-irradiated areas of the electron system are found to be rough on the scale of the Fermi wavelength [5, 6]. These observations lead to the assumption that the confining mechanism in ion-beam-defined structures is different from that in those patterned by other techniques. It is believed that defects created by the ion beam irradiation in the plane of the electron system act as short-range scatterers at the boundary between irradiated and non-irradiated areas.

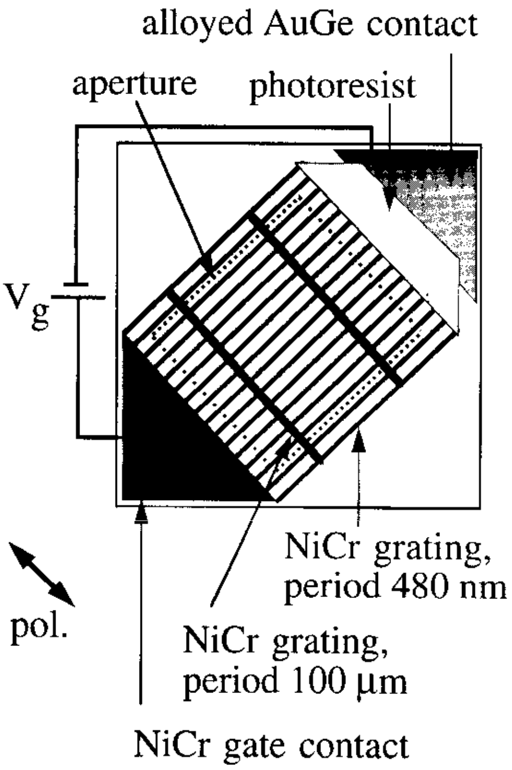

Figure 1. Schematic sketch of the sample surface after processing. It is covered by approximately 4000 NiCr stripes with a period of 480 nm, and—perpendicular to these—20 NiCr stripes with a period of 100 μm. The AuGe contact is alloyed to the electron system 60 nm below the surface. White areas become insulating during irradiation. The dotted line indicates the area (about (2 mm)^2), which is illuminated by FIR radiation. The polarization of the radiation is also indicated.

We examined the FIR conductivity of the wire array in a rapid-scan Fourier transform spectrometer at a temperature of 2 K and different magnetic fields ranging from 0 to 10 T. The differential FIR spectra presented in the following are evaluated from two transmission spectra taken at different gate voltages according to $\Delta T = T(V_g)/T(V_{ref})$, where no mobile electrons reside in the device at V_{ref}. The change in the relative transmission $1 - \Delta T$ is approximately proportional to the frequency-dependent conductivity. A capacitance–voltage measurement reveals that below the threshold voltage $V_{th} = -1.4$ V all electrons beneath the gate are depleted. The reference gate voltage is chosen to be $V_{ref} = -1.5$ V. The FIR radiation is incident normal to the sample surface and polarized normal to the electron wires, to excite only oscillations perpendicular to the wires.

3. Results and discussion

In figure 2 FIR spectra taken at zero magnetic field and different gate voltages are depicted. The strong resonance observed at zero gate voltage at $\omega_0 = 39$ cm^{-1} is the fundamental collective excitation in electron wires in radiation fields polarized perpendicular to the wires. It results from the oscillatory centre-of-mass motion

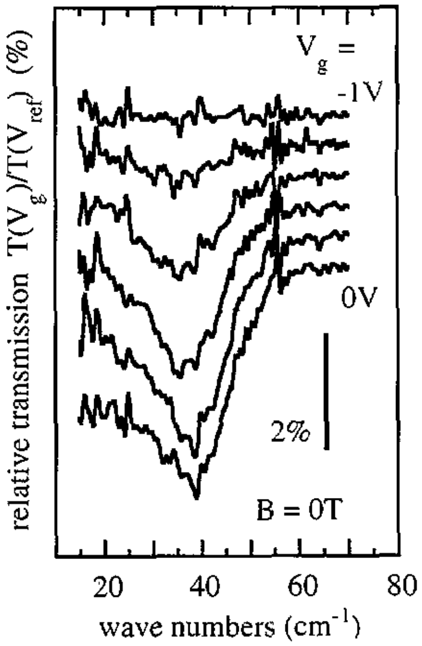

Figure 2. Relative far-infrared transmission spectra at zero magnetic field and $T = 2$ K in the frequency range of the fundamental dimensional resonance. The spectra are offset for clarity and the gate voltage is increased in steps of 0.2 V. The reference gate voltage is set up to -1.5 V where no electrons reside in the device.

of the electron systems in the individual wires excited by the perpendicularly polarized incident FIR radiation. The resonance position only decreases slightly with decreasing gate voltage. The resonance linewidth is very large (approximately 17 cm^{-1}) compared with those found in purely field-effect-induced electron wires [8, 10] and dominated by the ion-beam-induced boundary roughness scattering [6]. It is clearly visible that within the experimental error the gate voltage only affects the amplitude, not the full-width at half-maximum (FWHM) (see also inset of figure 3). The boundary roughness of the ion-beam-defined wires is obviously not reduced by the potential induced by the biased gate. This is a further proof that the electronic wire width is not changed noticeably by the voltage applied at the self-aligned gate.

We wish to compare this result with the behaviour of the dimensional resonances in an ion-beam-defined wire system with a distance-modulated gate which was investigated in [6] (see figure 7 in [6]). There a photoresist grid served as a mask for the ion beam irradiation. The widths of those photoresist stripes were 280 ± 30 nm and hence were in the same range as the metal masks employed here. A homogeneous gate was evaporated on the crystal surface after the Ne irradiation without removing the photoresist stripes. Thus, above the ion-beam-defined wires the distance between the gate and the electron system was enlarged by the photoresist mask whereas in the regions between the wires the gate was located directly on the crystal surface. Hence, similar to the action of a split gate with the gap aligned above the wire, the electrons in the wire are pushed away from the rough ion-beam-defined boundaries when a negative gate voltage is applied. As a consequence the dimensional resonance linewidth reduces by a factor of two, if a negative gate voltage of $V_g = -200$ mV with respect to the electron system is applied. Thus, a gradual transition from rough ion-beam-defined to smooth field-effect-defined wire boundaries is observed. This is in agreement with DC magnetotransport studies on single-wire systems showing that the boundary scattering in purely field-effect-defined wires is specular to a higher degree than in ion-beam-defined wires [3]. Contrary to this, in samples with gate electrodes perfectly aligned above the ion-beam-defined wires, as used here, obviously no such mechanism is working and, hence, the resonance linewidth remains constant with changing gate voltage (see inset of figure 3).

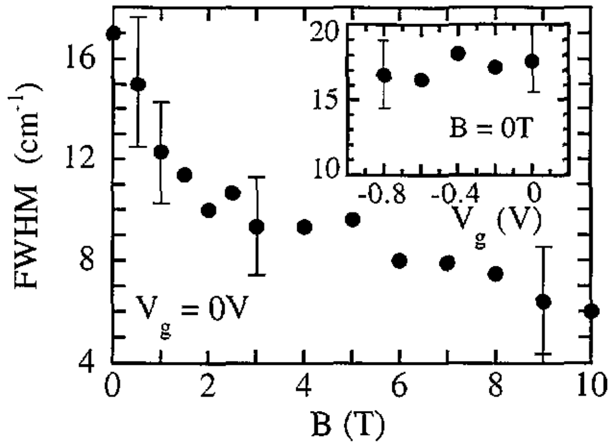

Figure 3. Full-widths at half-maximum (FWHM) of the fundamental absorption line measured with zero gate voltage at different magnetic fields on an ion-beam-defined electron wire array. The inset shows the FWHM of the fundamental zero-magnetic-field resonance for different gate voltages.

We would now like to discuss the behaviour of the resonance linewidths of the fundamental mode at different magnetic fields from which we determine the impact of the boundary roughness on the resonance linewidth [6]. In figure 3 the FWHM of the resonances at $V_g = 0$ V are depicted. In agreement with the results in [6] the linewidth reduces approximately by a factor of three at high magnetic fields. This behaviour can be understood by the fact that in high fields the electron motion becomes more cyclotron like. While the dimensional resonance at low magnetic fields is strongly damped by diffuse boundary scattering processes, the linewidth considerably reduces, when an increasing number of the classical electron trajectories are localized within the channel by high magnetic fields and thus have less boundary contact.

Spectra taken at different magnetic fields normal to the sample surface and at a gate voltage $V_g = 0$ V are shown in figure 4. Aside from the fundamental excitation indicated by full circles a second resonance is visible with much smaller oscillator strength and positions indicated by full triangles. We identify this absorption with a higher-order dimensional resonance [10, 11]. According to the generalized Kohn theorem [12, 13], in wire systems with purely parabolic

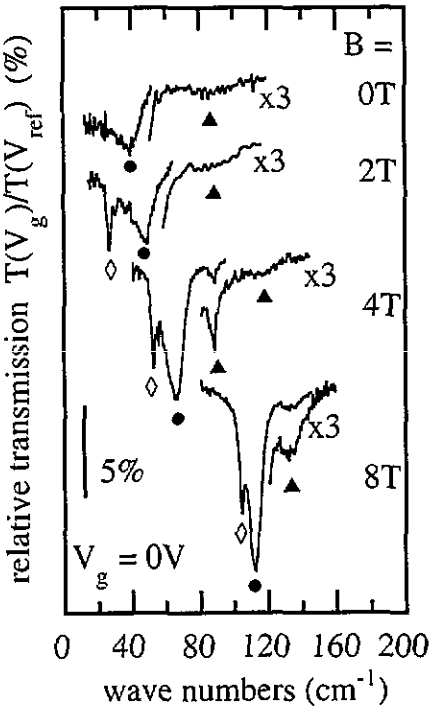

Figure 4. Relative far-infrared transmission spectra recorded at $T = 2$ K, zero gate bias and different magnetic fields on an ion-beam-defined electron wire array. The high-frequency parts of the spectra are enlarged by a factor of three. The different symbols denote the different kinds of excitations: fundamental dimensional resonance (●), higher-order dimensional resonance (▲) and the cyclotron resonance resulting from the two-dimensional regions of the sample (◇).

confinement a homogeneous excitation field would excite only the fundamental mode. We do not expect strong radiation field inhomogeneities for the excitation of higher-order modes since the crystal surface is hardly affected by the ion beam irradiation process and the gate metal is thin and perfectly aligned above the wires. Thus the occurrence of higher-order resonances reflects the presence of non-parabolic contributions to the confinement potential. In systems with non-parabolic contributions to the potential at zero magnetic field the spectral position of the third-order dimensional resonances can be expected at $\omega = \sqrt{3}\omega_0$, the fifth at $\omega = \sqrt{5}\omega_0$ [11, 14]. Even-order resonances are not expected to be seen in this experiment as a consequence of their vanishing dipole moment [10, 11]. At $B = 0$ T the higher-order resonance is observed at a frequency of $\omega_1 = 86$ cm^{-1} and, accordingly, ω_1/ω_0 is approximately $\sqrt{5}$. Within the models in [11, 14] we would thus identify the observed high-frequency mode as the fifth-order resonance whereas the third-order resonance, that we would expect at a frequency of about 68 cm^{-1}, surprisingly is not resolved. At present, we lack a proper explanation of the frequency of the higher-order mode, but speculate that it might reflect the special properties of the confinement potential in ion-beam-defined electron wires.

Like the fundamental resonance the higher-order dimensional resonance sharpens with increasing magnetic field. On the wire systems in [6], which were prepared with the same irradiation technique, the higher-order resonance probably could not be observed because there the signal-to-noise ratio was limited by the fact that no gate voltage ratios were possible for the differential spectroscopy.

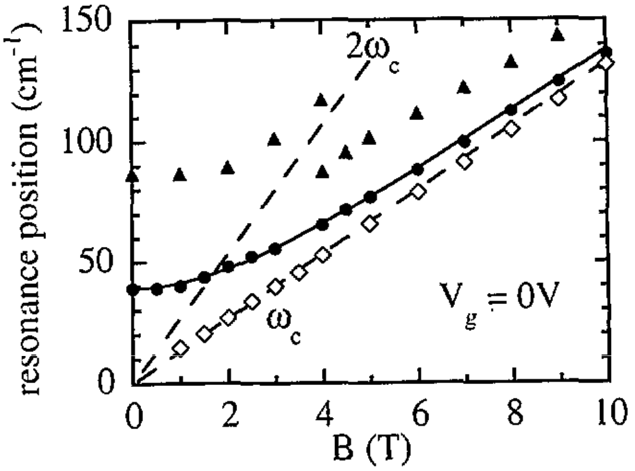

Figure 5. Magnetic field dependence of the resonance positions. The symbols are as in figure 4. The full curve is calculated according to $\omega_{res}^2 = \omega_0^2 + \omega_c^2$, with $\omega_0 = 39$ cm^{-1}, while the broken lines represent the first and the second harmonic of the cyclotron frequency.

As shown in figure 5, the frequency ω_{res} of the fundamental mode follows the relation $\omega_{res}^2 = \omega_0^2 + \omega_c^2$, previously found to well describe the magnetic field dispersion of dimensional resonances in electronic wire arrays [10, 15]. Here ω_c is the cyclotron frequency eB/m^*, with an effective electron mass $m^* = 0.07\ m_e$ for GaAs and $\omega_0 = 39$ cm^{-1}, taken from the experiment. The magnetic field dispersion of the higher-order mode exhibits a pronounced splitting at a frequency where the mode becomes degenerate with the second harmonic of the cyclotron frequency. Such a splitting of the higher-order mode is also observed in purely field-effect-induced wires [10] and has been related to the non-local interaction [16] observed for plasmons in 2D systems. Unlike in observations on purely field-effect-induced wire arrays [10], none of our spectra shows a splitting of the fundamental mode. In figure 4 a small absorption is visible at the position of the cyclotron frequency, which we relate to the two-dimensional regions of the sample beneath the large-period grating which is oriented perpendicular to the wire system as described above. The spectral position of all types of resonances is hardly affected by the gate voltage. Only the oscillator strengths decrease with decreasing voltage, reflecting the decreasing electron density in the wires. This observation is surprising considering the fact that the confinement potential in the ion-beam-defined wires is expected to be non-parabolic to a certain degree. For example, in a hydrodynamic model assuming a square-well potential the resonance position is expected to increase with the density [11]. We note that also for purely field-effect-induced wires with non-parabolic contributions to the confinement potential only a weak density dependence of the dimensional resonance positions is reported [10].

4. Conclusion

We investigated the high-frequency conductivity of ion-beam-defined wire structures in the FIR domain. The radiation field is polarized perpendicular to the wire stripes. In the samples investigated here the wire array is defined with a metal grating used as irradiation mask. In addition, the grating is employed as a self-aligned gate to field-effect tune the electron density in the experiment while the wire width is not significantly changed. We find that in these structures the resonance linewidth at zero magnetic field does not change with the electron density, demonstrating that the impact of the boundary roughness on the linewidth does not change with the electron density. This is in contrast to results obtained in structures with a distance-modulated gate where the electrons are squeezed away from the ion-beam-defined boundaries by applying a gate voltage to reduce the electron density. The potential formed by ion beam patterning of the wire array has significantly non-parabolic contributions, which manifest themselves in the observation of a higher-order dimensional resonance.

Acknowledgments

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