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Electro-optic voltage profiling of modulation-doped GaAs/AlGaAs heterostructures

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The electro-optic effect of GaAs is applied to profile the voltage distribution of the two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure. In our setup we reached a voltage sensitivity of 2 mV. We used this technique to characterize the local resistivity of the 2DEG. The results are consistent with those obtained from scanning electron microscopy voltage contrast measurements.

Modulation-doped GaAs/AlGaAs heterostructures are widely used to study two-dimensional transport phenomena. For the correct interpretation of experimental data of electrical transport measurements knowledge of the local potential of the two-dimensional electron gas (2DEG) at the GaAs/AlGaAs interface is of great importance.

The linear electro-optic effect or Pockels effect is extremely useful to measure voltages.¹⁻⁶ The measuring technique is based on the fact that the birefringency of the electro-optic crystal changes with the applied electric field. In the right experimental geometry this effect leads to a change of the polarization of light. This change of polarization can be measured with great accuracy.

In this letter we describe how the electro-optic effect of the semi-insulating (SI) GaAs substrate can be used to profile voltages in the 2DEG of a modulation-doped GaAs/AlGaAs heterostructure. We use this technique to determine the homogeneity of the conductivity of the 2DEG, which can show both abrupt and more gradual changes.⁷⁻⁹

The samples used in this study are selectively doped heterostructures grown by molecular beam epitaxy (MBE) on a SI GaAs substrate. The structures consist of a 5 μm GaAs buffer layer, a 36 nm undoped $\text{Al}_{0.38}\text{Ga}_{0.62}\text{As}$ spacer, a 31 nm Si-doped $\text{Al}_{0.38}\text{Ga}_{0.62}\text{As}$ layer, and a 24 nm GaAs cap layer. The mobility of the 2DEG is 0.82 (36) m^2/Vs and the electron concentrations 2.5×10^{15} (1.9×10^{15}) m^{-2} at 300 K (4.2 K).

A Hall bar configuration was photolithographically defined and mesa etched [see Fig. 1(a)]. The ohmic contacts were formed by alloying small In spheres into the surface [the black circles in Fig. 1(a)]. We polished the rear of the sample and subsequently evaporated a 100 Å layer of Au on it to maintain an equipotential plane as a reference for the potential of the 2DEG. For a current flowing through the 2DEG two electric field components are present: one parallel to the 2DEG and one between the 2DEG and the Au layer.

The experimental setup is depicted in Fig. 1(b). As a light source we use an InGaAsP diode laser with a wavelength λ of 1.3 μm and a power of 1 mW. The light is polarized by a Glann-Taylor polarizer and is subsequently fo-

cused on the sample to a spot of 40 μm . This spot can be moved across the sample by displacing the total optical setup with an xy stage.

The light polarized along the $\langle 100 \rangle$ axis is passed through the GaAs heterostructure along the $\langle 001 \rangle$ axis in the same direction as the electric field between the 2DEG and the Au layer. Only this perpendicular electric field gives a noticeable phase difference. In the described geometry the phase difference $\Delta\Gamma$ between the slow and fast axis is given by¹⁰

$$\Delta\Gamma = \frac{2\pi}{\lambda} n_0^3 r_{41} \int_0^d E_z(x,y,z) dz = \frac{2\pi}{\lambda} n_0^3 r_{41} V(x,y), \quad (1)$$

where n_0 and r_{41} are the refractive index and the component of the electro-optic tensor of the GaAs, d is the thickness of the substrate, $E_z(x,y,z)$ is the electric field along the z direction, and $V(x,y)$ is the potential difference between the reference electrode and the 2DEG at position (x,y) . From Eq. (1) it follows that the phase difference and the potential are directly proportional to each other and the potential of the 2DEG is measured. If a quarter-wave plate is used the intensity of the transmitted light depends linearly on the phase difference.¹⁰ To detect small variations in intensity we modulated the potential $V(x,y)$. This results in a modulated intensity of the transmitted light. This intensity variation is

FIG. 1. (a) Geometry of the samples used in this study. The black circles are the indium ohmic contacts. The dashed lines indicate the four voltage line scans [Figs. 2(a) and 2(b)]. The box displays the area of the sample which has been studied by SEM voltage contrast (Fig. 3). (b) The experimental setup for the electro-optic voltage probe experiment.

FIG. 2. (a) Potential of the 2DEG with respect to the Au layer at the rear, for contact 2 at 0.7 V and contact 9 connected to the Au layer, scanned along the dashed line I of Fig. 1(a). Following the lines II, III, and IV of Fig. 1(a), we obtain voltage profiles as indicated in (b). Lines II and III are almost flat, but line IV shows a step, which we associate with an interruption of the 2DEG.

detected with a photodetector and lock-in amplifier. r_{41} was measured by applying a known voltage between the 2DEG and the Au layer, without a current flowing through the 2DEG, and was about 1.48 pm/V. This result was also used to calibrate the experimental setup.

With the described experimental setup we obtained sensitivities of 2 mV, when the laser spot was kept at one position. When scanning over the sample some additional uncertainties of about the same order of magnitude in the measured potential are introduced due to variations in the transmission.

During the electro-optic experiments we kept contact 1 at 0.7 V and contact 9 at 0 V. When we scanned along line I of Fig. 1(a) we obtained the voltage profile given in Fig. 2(a). One observes that the slope of the curve in the lower part of the curve ($0 < y < 2.4$ mm) is steeper than in the upper part, implying a change in the resistance of about a factor of 2. In Fig. 2(b) the voltage profiles of lines II, III, and IV are depicted. A quite extraordinary step is found in line IV, where a drop of almost 0.25 V is present.

Intuitively we associated this step with an interruption of the 2DEG between contacts 8 and 9. This also then would explain the two different slopes of curve I. The current then would flow in the upper part through a 2-mm-wide region, while in the lower part the current flows through an approximately 1-mm-wide region with a higher resistance.

To check this interpretation we performed a scanning electron microscopy (SEM) voltage contrast measurement,^{7,11} which in a different way also measures the electrical potential of the surface. The primary electron beam of the scanning electron microscope generates secondary electrons. The number of secondary electrons detected strongly depends on the surface potential. An area with a positive potential appears dark on the monitor while a negative area appears bright. In Fig. 3 a SEM voltage contrast image of the part of the sample enclosed by the box [Fig. 1(a)] is shown. We held contact 2 at 0 V and contact 9 at 2 V. One immedi-

FIG. 3. SEM voltage contrast image of the part of the sample within the box which is indicated in Fig. 1(a). Contact 2 is at zero voltage while contact 9 is kept at 2 V. The dark regions are associated with a large positive value while the lighter regions have smaller values. Clearly visible is the step in potential between contacts 8 and 9.

ately observes the sharp contrast between contacts 8 and 9 indicating a large potential difference. This contrast exactly coincides with the potential drop we found with the electro-optic experiments. It is also clear that this interruption stops almost 2 mm above the lower contacts, confirming that the resistance of the lower part of the sample is larger than in the upper part. It is also interesting to note that the interruption of the 2DEG is exactly parallel to the $\langle 110 \rangle$ crystal axis. We have already reported on this feature earlier.⁷ Since these interruptions are both present in MBE and metalorganic chemical vapor deposition material, they probably arise from an imperfection in the substrate.

The main advantage of the electro-optic voltage profiling above SEM voltage contrast is that there is almost no influence of the measuring system on the device. Furthermore, the electro-optic measuring technique is extremely well suited to be used at low temperatures and in high magnetic fields. This makes it possible to tackle, for example, the fundamental problem of current and potential distribution under quantum Hall conditions.^{12,13}

In conclusion, we used the electro-optic effect of the GaAs substrate to profile the potential of the 2DEG of a GaAs/AlGaAs heterostructure. Furthermore, we showed how this technique is a powerful tool to characterize GaAs/AlGaAs heterostructures.

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