Kelvin Probe Spectroscopy of a Two-Dimensional Electron Gas Below 300 mK

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A scanning force microscope with a base temperature below 300 mK is used for measuring the local electron density of a two-dimensional electron gas embedded in a Ga[Al]As heterostructure. At different separations between AFM tip and sample, a dc-voltage is applied between the tip and the electron gas while simultaneously recording the frequency shift of the oscillating tip. Using a plate capacitor model the local electron density can be extracted from the data. The result coincides within 10% with the data obtained from transport measurements.

The electron density of two-dimensional electron gases (2DEGs) is usually determined by magnetotransport experiments. The carrier density can be either extracted from the low-field slope of the Hall resistance or from the 1/B periodicity of Shubnikov-de Hass oscillations. Also C–V profiling and magnetocapacitance experiments are versatile tools to detect the electron density in an electron gas located below a metallic top gate electrode.

Here we set out to use a Kelvin probe technique in order to measure the local electron density in a 2DEG below the conductive tip of an atomic force microscope. The two-dimensional electron gas investigated is embedded in a Ga[Al]As heterostructure with the electrons buried 40 nm below the surface. No mesa structure was imprinted. Ohmic contacts at the sample edges allow to measure the 4-terminal resistances at low temperatures and to determine the carrier density through transport measurements.

The sample is mounted in a home built scanning probe microscope (SPM) situated in a ³He-cryostat where an operating temperature below 300 mK is reached routinely. Scanning is performed with an electrochemically etched metallic tip attached to the end face of one prong of a piezoelectric quartz tuning fork. Optical detection of the cantilever deflection is not suitable for our purposes, because the sample’s electronic properties are sensitive to light (persistent photoeffect). Therefore the setup relies on a piezoelectric measurement of the tip oscillation utilizing a phase-locked loop measuring the change in resonance frequency upon changes in the tip-sample interaction. The relative accuracy of the frequency detection is better than 10⁻⁷.

In a dynamic mode SPM at small tip oscillation amplitudes, the measured frequency shift ∆f does not directly reflect the force Fts acting on the cantilever, but rather the force gradient

\[ \Delta f \propto \frac{dF_{ts}}{dz} : = F'_{ts}. \tag{1} \]

By applying a dc-voltage between the metallic tip and the sample, the density is modified. In a metallic system one expects a parabolic voltage dependence of the force gradient. The curvature of the parabola is determined by the capacitive coupling between tip and sample. The position of the apex of the parabola determines the contact potential difference UCPP of the two metals. This method is generally known as Kelvin probe.

Figure 1 shows Kelvin probe data measured at different tip-sample distances with a 2DEG underneath the tip. The curvature of the measured curves is different for positive and negative voltages as indicated by the fit to the 9 nm curve. The reason lies in the depletion of the 2DEG, i.e., a negative voltage indicates that the negative contact is connected to the electron gas.

![Figure 1: Kelvin probe at different tip-sample distances.](image)

The electrostatic force gradient F'_{ts} between tip and sample responds to a change in the bias voltage U as

\[ F'_{ts} = \frac{1}{2} \frac{d^2C(z,U)}{dz^2}(U - UCPP)^2, \tag{2} \]

where C(z,U) is the tip-sample capacitance. For metallic...
The knee line is a linear fit to the data. One capacitor plate, the tip, resides at a distance $z$ above the sample surface. The two-dimensional electron gas is buried underneath a GaAs cap layer of thickness $D$. The dielectric constants are $\epsilon_1 = 1$ for the vacuum and $\epsilon_2 = 12$ for GaAs, respectively (see inset in Fig. 3a).

For $U < U_{\text{depl}}$ the total capacitance $C_{\text{tot}}(z)$ is assumed to be independent of voltage and given by

$$\frac{C_{\text{tot}}(z)}{A} = \frac{\epsilon_0 \epsilon_1 \epsilon_2}{\epsilon_2 z + \epsilon_1 D},$$

where $A$ is the area of the plates.

The charge density in the 2DEG is given by

$$\epsilon n_s(U) = \frac{\Delta Q}{A} = -\frac{C_{\text{tot}}}{A} (U - U_{\text{CPD}}) + \epsilon n_s^{(0)},$$

where $n_s^{(0)}$ is the charge carrier density for $U = U_{\text{CPD}}$ and $n_s(U)$ is the voltage dependent charge carrier density in the 2DEG underneath the tip.

For total depletion under the tip $n_s(U_{\text{depl}}) = 0$ and the depletion voltage is

$$U_{\text{depl}} = U_{\text{CPD}} + \frac{\epsilon n_s^{(0)}}{\epsilon_0 \epsilon_1 \epsilon_2} (\epsilon_1 D + \epsilon_2 z),$$

i.e. there is a linear dependence between depletion voltage and tip-sample separation $\Delta z$. The free parameter determining the slope of $U_{\text{depl}}(z)$ is the electron density $n_s^{(0)}$ of the 2DEG.

From the data plotted in Fig. 3a, a local electron density of $n_{\text{local}} = 1.9 \times 10^{15} \text{ m}^{-2}$ is extracted from the slope of the data points. This compares to the electron densities gained from Shubnikov-de Haas and Hall transport measurements. They are $n_{\text{Hall}} = 1.70 \times 10^{-15} \text{ m}^{-2}$ and $n_{\text{SHH}} = 1.56 \times 10^{-15} \text{ m}^{-2}$. The corresponding curves in Fig. 3a have been generated using equation (3).

The three results differ slightly. Considering that the methods and scopes of the three measurements are different, this is not unexpected. The local measurement probes the local properties of the electron gas right underneath the tip whereas transport measurements average over the whole sample area. Scanning electron microscope images of the tip performed after warming suggest a tip radius $R$ in the range of 1 $\mu$m. This is more than an order of magnitude larger than the average tip-sample separation and hence the plate capacitor model is justified.

When talking about local measurements, the question of the lateral resolution arises. We have not yet performed scanning capacitance experiments with the described method, but as the method relies on $R \gg \Delta z$ the resolution will be limited by the tip-radius $R$.

The contact potential difference $U_{\text{CPD}}$ between the PtIr-tip and the 2DEG can be extracted from positions of the maxima of the fitted parabolae. In Fig. 3b we plot $U_{\text{CPD}}$ versus the tip-sample separation. There is a slight decrease of $U_{\text{CPD}}$ with $\Delta z$. The typical value for $U_{\text{CPD}}$ for a PtIr-heterostructure system is 0.5 V as measured. This value is important because it has to be taken into account in non-invasive electronic measurements.

Only the high stiffness of a tuning fork oscillator allows for the presented measurements. Although softer cantilevers suggest a higher force resolution, they bend with attracting forces and $\Delta z$ would no longer be constant. At higher forces the tip on a soft cantilever would
FIG. 3: a) Depletion voltage plotted versus the tip-sample distance at which the Kelvin probe was recorded. The electron density extracted from the transport data is $n_{\text{Hall}} = 1.70 \times 10^{11} \text{ cm}^{-2}$ and $n_{\text{SdH}} = 1.56 \times 10^{11} \text{ cm}^{-2}$. This leads to the solid lines in the graph. Inset: Model geometry. b) Contact potential difference $U_{\text{CPD}}$ plotted as a function of $\Delta z$.

even stick to the sample in what is generally known as “snap-in”.

A general model not reproduced here involving doping ions and surface charges adds a distance dependence to the expression for $U_{\text{CPD}}$. Reducing it to a plate capacitor cancels out this dependence.

In conclusion, we have performed low-temperature local Kelvin probe measurements on a Al[Ga]As heterostructure using a tuning fork based scanning probe microscope. With the help of a plate capacitor model the local electron density underneath the tip could be determined.

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[1] T. Ambridge, C. R. Elliott and M. M. Faktor, J. Appl. Electrochem., 3, 1 (1973)
[2] P. Blood P, Semicond.Sci.Tech. 17 (1986).
[3] P. J. Baxandall, D. J. Colliver, and A. F. Fray, J.Phys.E: Scient.Instrum. 4 213 ( 1971).
[4] J. A. Copeland, IEEE Trans.Electron.Devices 15, 761 (1969).
[5] V. Mosser, D. Weiss, K. von Klitzing, K. Ploog, and G. Weimann, Sol.Stat.Com. 58 1 (1986).
[6] T. H. Smith, B. B. Goldberg, M. Heiblum, and P. J. Stiles, Surf.Sci. 170 304 (1986).
[7] T. Ihn, Electronic Quantum Transport in Mesoscopic Semiconductor Structures, Springer Tracts in Modern Physics, Springer Verlag, Vol. 192, 2003.
[8] P. Gütthner, U. Ch. Fischer, and K. Dransfeld, Appl. Phys. B 48, 89 (1989).
[9] K. Karrai and R. D. Grober, Appl. Phys. Lett. 66, 1842 (1995).
[10] H. Edwards, L. Taylor, W. Duncan, and A. J. Melmed, Jour.Appl.Phys. 82, 980 (1997).
[11] J. Rychen, T. Ihn, P. Studerus, A. Herrmann, K. Ensslin, H. J. Hug, P. J. A. van Schendel and H. J. Güntherodt, Appl. Surf. Sci., 157, 290 (2000).
[12] F. J. Giessibl, Appl. Phys. B 76, 1470 (2000).
[13] T. R. Albrecht, P. Grütter, D. Horne and D. Rugar, Jour.Appl.Phys. 69, 668 (1991).
[14] U. Dürig, O. Züger, and A. Stalder, J. Appl. Phys. 72, 1778 (1992).
[15] J. Rychen, T. Ihn, P. Studerus, A. Herrmann, K. Ensslin, H. J. Hug, P. J. A. van Schendel and H. J. Güntherodt, Rev.Sci.Instr, 71, 1695 (2000).
[16] M. Nonnenmacher, M. P. o’Boyle, and H. K. Wickramasinghe, Appl. Phys. Lett. 58, 2921 (1991).
[17] H. O. Jacobs, H. F. Knapp, and A. Stemmer, Rev.Sci.Instr 70, 1756 (1999).
[18] W. Nabhan, B. Equer, A. Broniatowski, and G. De Rosny, Rev.Sci.Instr 68, 3108 (1997).