Invited Paper

Corbino–Capacitance Technique for Contactless Measurements on Conducting Layers – Application to Persistent Photoconductivity

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ABSTRACT

The technique utilizes the capacitive coupling between a pair of Corbino electrodes and a conducting layer placed on top of, and insulated from, the electrodes. Measurements on heterostructures of GaAs/GaAlAs and GaAs/GaInP are reported. The audio–frequency impedance exhibits Shubnikov–deHaas oscillations. These oscillations are used to investigate persistent photoconductiity at 0.635 μm and 1.00 μm illumination. The role played by contacts is discussed.

1. INTRODUCTION

The conventional sample geometries: Hall bar, van der Pauw, and Corbino, have one feature in common, namely the attachment of contacts and leads, and hereby the possibility of exchange of charge carriers between the sample and the surroundings. The contactless Corbino–capacitance technique is different: the surroundings couple to the sample charge carriers only via electromagnetic fields, i.e. the sample can be viewed as a subsystem with a conserved number of particles. The technique was suggested by Templeton.[1]

Below we present an investigation of GaAs/GaAlAs and GaAs/GaInP heterostructures, making first a comparison between results obtained by the contactless Corbino and the conventional Hall bar.

When using the contactless technique to investigate persistent photoconductivity in heterostructures we have expecially in mind the suggestion by Kastalsky and Hwang[2] that electrons excited from DX centres will penetrate into the high mobility channel through the contacts. This possibility does not exist in the present contactless technique.

2. THE CORBINO SAMPLE CONFIGURATION AND THE AC–BRIDGE

In fig. 1 we show a sketch of the Corbino electrodes and the ac–bridge. The electrodes (fig. 1a) are made from a piece of printboard. The centre disk has a diameter of 2.0 mm while the surrounding ring has inner and outer diameters of 2.5 mm and 3.4 mm respectively. Leads are soldered from beneath to the centre disk and to the ring.

During measurements the sample is placed on top of the Corbino electrodes (fig. 1b), held by photoresist, and with the GaAs substrate upwards. The Corbino sample system is placed in a superconducting solenoid producing a magnetic field B perpendicular to the sample. The system constitutes the unknown impedance Z_x in the ratio arms bridge[3] shown in fig. 1c.

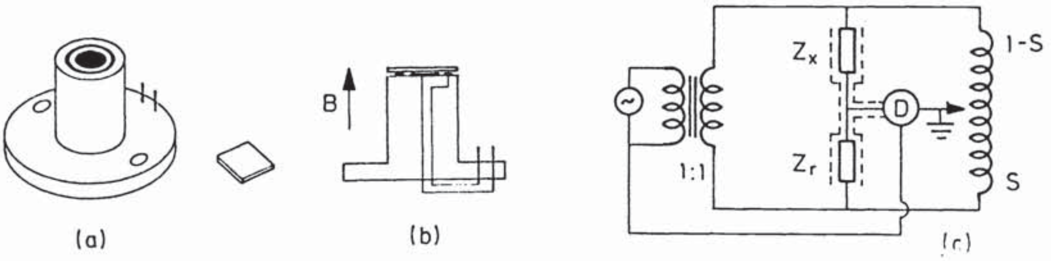

Figure 1: (a) The Corbino electrodes and the sample. (b) The mounted sample and the direction of the magnetic field. (c) The ac–bridge.

The bridge detector is a two–phase lock–in amplifier (EG&G 5206). A five decade ratiotransformer (inductive voltage divider) is used to generate the ratio (1–S)/S. The reference capacitance, Z_r, is a 10 pF, three terminal capacitor. The oscillator terminal voltage was usually set at 10 V peak–to–peak, and frequencies in the range 2.5 kHz to 20 kHz were used. If the ratio Z_x/Z_r is real, then the bridge is balanced by the setting S_o where

$$\frac{Z_x}{Z_r} = \frac{1 - S_o}{S_o}. \tag{1}$$

As the unknown impedance Z_x consists of the capacitance of the two Corbino electrodes coupled capacitively to the electrons in the heterostructure, Z_x is not a pure capacitance, and only one of the two phase channels of the lock–in implifier can be nulled. The other channel will display a voltage, V_D. This voltage is recorded as a function of the magnetic field B. Measurements were made at liquid helium temperatures.

3. LIGHT SOURCES AND SAMPLES

As light source was used either a red 0.635 μm light emitting diode (LED) or a halogen lamp followed by a monochromator.In the latter case the light was guided to the sample using an optical quarts fiber. The monochromator was set at 0.635 μm and 1.00 μm, corresponding to photon energies of 1.95 eV and 1.24 eV. The LED as well as the end of the optical fiber was placed a few mm above the sample, facing the GaAs substrate.

The GaAs/GaAlAs sample was cut from a wafer bought from Picogiga and specified as follows: MBE–grown 10 nm n^+ GaAs cap layer doped with $2 \cdot 10^{18}$ Si/cm^3, 35 nm $Al_{0\cdot28}Ga_{0\cdot72}As$ with the same Si–doping, 15 nm undoped $Al_{0\cdot28}Ga_{0\cdot72}As$, and finally a 1 μm thick undoped (p–) GaAs buffer layer grown on top of a LEC GaAs undoped substrate. The total thickness is 630 μm. The Al–mole fraction corresponds to an energy gap of 1.85 eV.

The GaAs/GaInP sample was grown by MOCVD at Thomson–CSF with 300 nm undoped GaInP and 500 nm undoped GaAs on a semiinsulating GaAs substrate. The GaInP energy gap is 1.9 eV.

4. MEASUREMENTS AND INTERPRETATION OF V_D VERSUS B

Fig. 2a shows V_D versus B for the GaAs/GaAlAs sample measured in the dark at 1.3 K. For comparison we present in fig. 2b the result of Hall bar measurements of ρ_{xx} on a sample cut from the same wafer. The ρ_{xy} measurements (not shown) clearly display integer quantum Hall plateaus.

We note that the two curves closely follow each other. Each time V_D peaks there is a dip in ρ_{xx}. As an example, the weak peak/dip at 3.6 T corresponds to five filled Landau levels (spin degeneracy included).

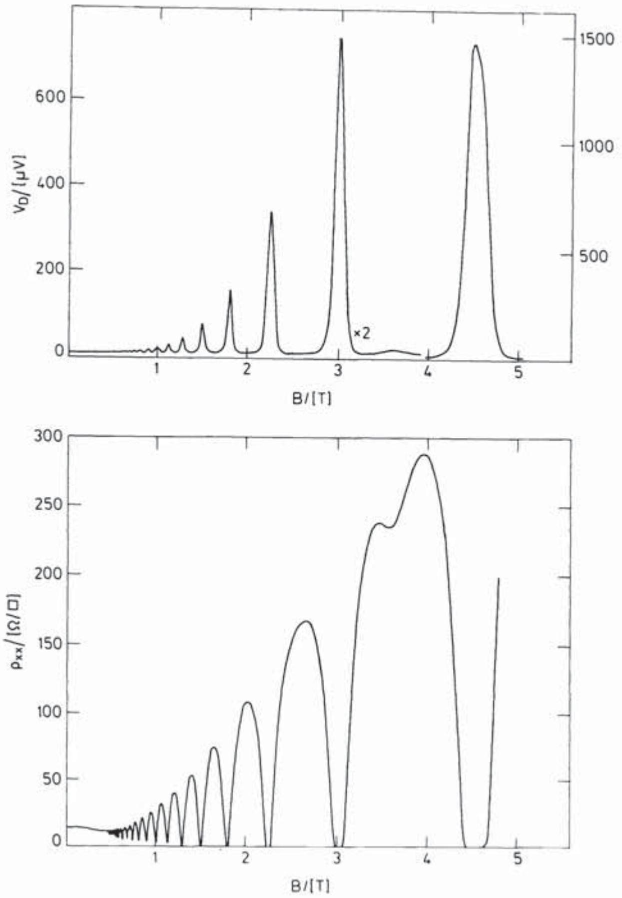

Figure 2: Measurements in the dark at a temperature of 1.3 K on GaAs/GaAlAs samples cut from the same wafer. (a) Bridge imbalance, V_D, in a Corbino measurement. The ac–frequency is 10 kHz, and the oscillator voltage is 10 $V_{P\text{-}P}$. Shubnikov–deHaas analysis gives a carrier density of $4.3 \cdot 10^{15}$ m^{-2}. (b) The longitudinal square resistance, ρ_{xx}, of a Hall bar mesa. The dc transport current is 52.5 μA. The values of the carrier density and the mobility has been determined to be $4.4 \cdot 10^{15}$ m^{-2} and 99 m^2/Vs respectively.

The above observation we interpret as follows: V_D is a measure of the inverse diagonal conductivity, and this is related to the resistivity elements in the usual way

$$V_D \sim \frac{1}{\sigma_{rr}} = \frac{\rho_{rr}^2 + \rho_{r\theta}^2}{\rho_{rr}}, \tag{2}$$

so, as $\rho_{r\theta}$ takes on one of the quantum Hall plateau values, and simultaneously ρ_{rr} becomes very small, V_D will peak at the ρ_{rr}–minima,

$$V_{D,peak} \sim \frac{\rho_{r\theta}^2}{\rho_{rr}}. \tag{3}$$

At the ρ_{rr}–minima the Hall angle approaches $\pi/2$, and this implies that the Corbino current path changes from being roughly radial to become spiral–like, almost circular.

In accordance with this interpretation, carrier densities are found from Shubnikov–deHaas analysis (inverse magnetic field versus V_D–peak number).

In fig. 3 is shown a V_D–trace for the GaAs/GaInP sample in the dark at 4.2 K. Shubnikov–deHaas analysis gives a carrier density of $5.3 \cdot 10^{15}$ m^{-2}. The control measurement in this case was made on a van der Pauw geometry, resulting in a carrier density of $5.8 \cdot 10^{15}$ m^{-2} and a mobility of 11 m^2/Vs.

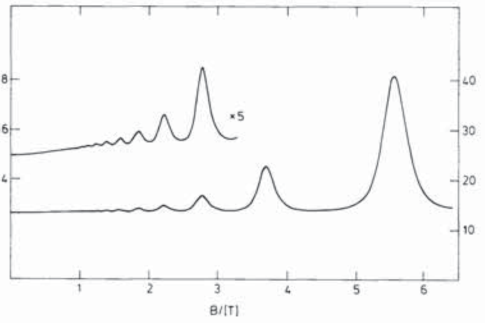

Figure 3: The bridge imbalance, V_D, in a Corbino–measurement on the GaAs/GaInP sample performed at a temperature of 4.2 K in the dark. The ac–frequency was 20 kHz, and the oscillator voltage 10 $V_{p\text{-}p}$. Shubnikov–deHaas analysis gives a carrier density of $5.3 \cdot 10^{15}$ m^{-2}.

5. PERSISTENT PHOTOCONDUCTIVITY

The measurements displayed in fig. 2 and 3 were made in the dark. It was, however, observed that exposure to light, 0.635 μm as well as 1.00 μm, changed the SdH–pattern of V_D versus B in a persistent and accumulative way. After each exposure, the subsequent magnetic field sweep showed a shift towards higher fields of the SdH–pattern.

5.1. The GaAs/GaAlAs sample and the Kastalsky–Hwang suggestion

Results for the GaAs/GaAlAs sample are shown in fig. 4 with the accumulated illumination time as parameter. The wavelength in this case is 0.635 μm from the monochromator. Similar results were obtained using a red LED.[4] A distinct splitting of the peaks is noted: after 6 minutes of accumulated illumination, the shifted dark–peak–pattern stops shifting, while a split–off pattern continues to shift. Apart from a transition region characterised by "shoulders" both patterns display welldefined SdH–periods. Carrier densities derived from the SdH–periods are shown in fig. 6. The splitting is seen to develop after approximately 2% increase of carrier density. We note that 0.635 μm light falling on the GaAs substrate is expected to be fully absorbed here.

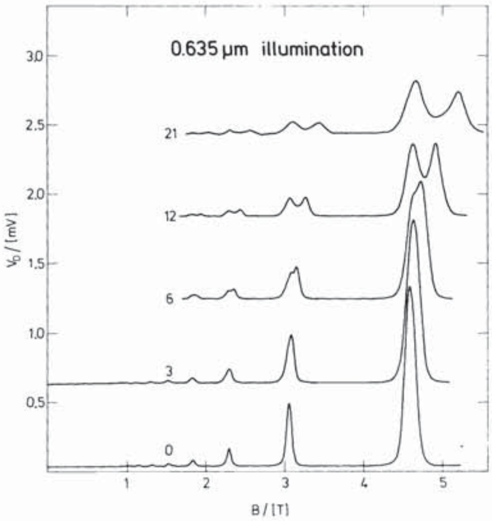

Figure 4: GaAs/GaAlAs sample exposed to 0.635 μm light from monochromator. Accumulated illumination times in minutes are written at each curve. The vertical scale only apply to the dark–curve; the other curves are each shifted a bit upwards in order that they can be seen separately. Temperature 4.2 K.

In fig. 5 we show the results for 1.00 μm illumination from the monochromator. The corresponding SdH carrier densities are displayed in fig. 6. At the largest accumulated illumination time the carrier density is 4% above its dark–value, and the V_D versus B curve shows a weak asymmetry of its peaks. We note that the 1 μm photons are incapable of bandgap excitations in the GaAs substrate, and expect them to reach the GaAlAs. The gradual way in which the SdH–patterns of fig. 5 evolve as the illumination time increases, strongly indicate that photoexcited electrons arrive into the high mobility 2D layer.

Considering the two mechanisms for the persistent photoconductivity suggested by Kastalsky and Hwang[2]: (i) DX center ionization in the GaAlAs and subsequent electron penetration into the 2D layer through contacts and (ii) electron–hole generation in GaAs followed by charge separation at the heterojunction, it seems that both of them can be excluded. However, a third mechanism: ionization of EL2 centres in the GaAs, may be considered as a possibility.

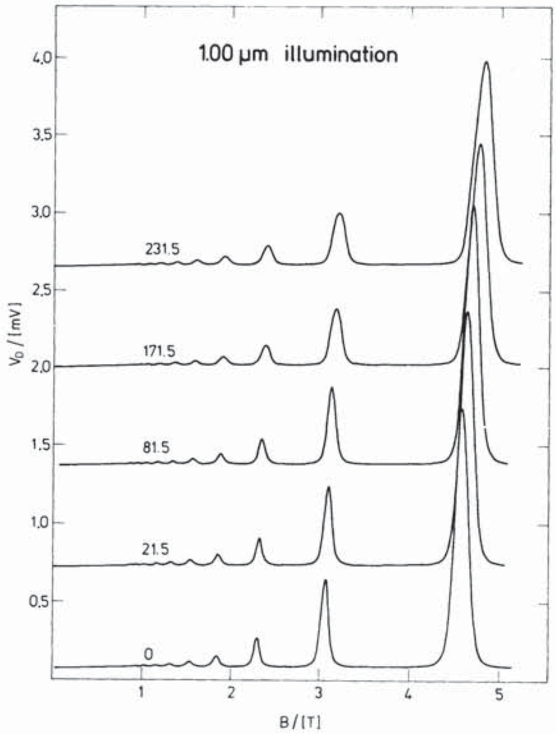

Figure 5: GaAs/GaAlAs sample exposed to 1.00 μm light from monochromator. Accumulated illumination times in minutes are written at each curve. The vertical scale only apply to the dark–curve; the other curves are each shifted a bit upwards in order that they can be seen separately. Temperature 4.2 K.

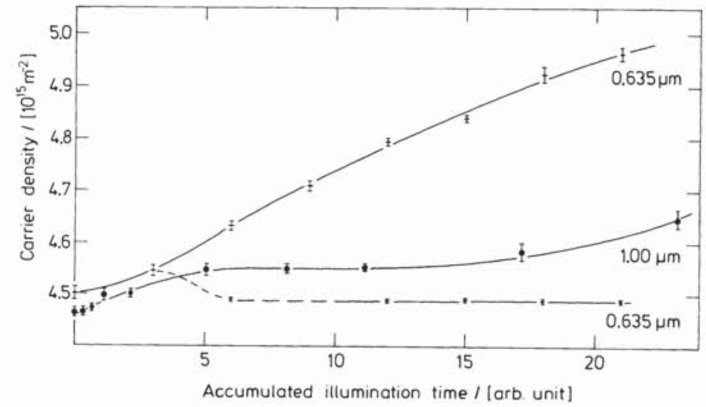

Figure 6: Carrier densities from SdH–analysis of V_D versus B^{-1}. Crosses: 0.635 μm illumination, dots: 1.00 μm, illumination.

5.2. The GaAs/GaInP sample

Results for the GaAs/GaInP sample are shown in fig. 7. A red LED was used as light source.

Although, apparently, the V_D–peaks shift with illumination in a way analogous to the GaAs/GaAlAs sample, the SdH analysis reveals no increase, within 1%, of carrier density.

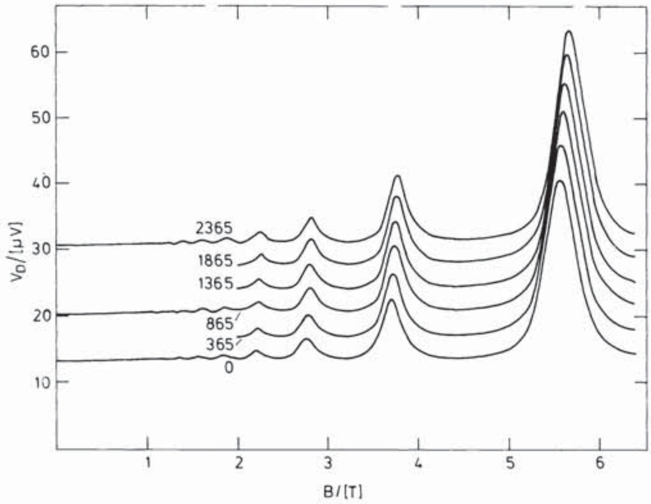

Figure 7: GaAs/GaInP sample exposed to 0.635 μm light from LED. Accumulated illumination times in μs are written at each curve. The vertical scale only apply to the dark–curve; the other curves are each shifted a bit upwards in order that they can be seen separately. Temperature 4.2 K.

6. CONCLUSION

In the GaAs/GaAlAs sample a persistent photoconductivity is generated by illumination with a wavelength of 0.635 μm as well as of 1.00 μm. The 0.635 μm light gives rise to a splitting of the peaks in the SdH–pattern of V_D versus B.

As regards the role of contacts, the 1 μm results show that photoexcited electrons either (i) originate from DX centers in the GaAlAs from where they reach the 2D layer even when no contacts are present or (ii) they originate from EL2 centers in the GaAs.

The 0.635 μm illumination of the GaAs/GaInP sample results in a shifted SdH–pattern of V_D versus B. However, this shift does not correspond to a measurable increase of carrier density.

7. REFERENCES

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