Contactless Electron Mobility Evaluation of Semi-Insulating GaAs and InP Wafers

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Abstract

An innovative procedure to evaluate the electron mobility of semi-insulating GaAs and InP wafers is presented. It is based on a capacitive contactless technique previously developed for resistivity mapping (COREMA). The measurement is consecutively performed with and without a magnetic field. The correlation with Hall data is satisfactory, whereas the agreement with calculated drift mobility is excellent. The new technique is superior to the conventional procedure in regard of cost, speed, nondestructiveness, reproducibility and lateral resolution. A system design meeting the requirements of eventual routine industrial application is described.

INTRODUCTION

Semi-insulating GaAs and InP wafers, used to fabricate microwave and high speed digital circuits, are routinely characterized with respect to the electrical resistivity ρ and the carrier mobility μ. As a rule the vendor uses test wafers taken from the seed and the tail of the single crystal ingots to obtain the absolute values and variation ranges. The established Hall evaluation technique requires to cut square samples out of test wafers, then to form Ohmic contacts and bond wire or needle contacts. These preparations and the subsequent measurements are time-consuming and destructive, allowing to obtain only some few localized data from sacrificed test material.

In recent years an innovative contactless resistivity mapping technique (COREMA, originally referred to as TDCM), using a capacitive transient charge measurement, has been developed [1]. This technique, briefly described below, is presently used by substrate fabrication companies for routine material quality assurance and is supporting exploratory material research in academic institutes [2-4].

However, a significant drawback of standard COREMA has been that it does not allow to measure μ. Hence, while substantial improvement, acceleration and cost reduction of the ρ evaluation was provided, the Hall measurement was not entirely substituted and, therefore, still had to be done in addition to the COREMA evaluation. We report on a decisive upgrading of COREMA [5] which allows to evaluate both ρ and μ, thus providing the full set of electric transport parameters. Comparative measurements will be presented for GaAs only, but the method is likewise applicable to semi-insulating InP.

EXPERIMENTAL PROCEDURE

The basic COREMA procedure [1] is briefly reviewed here. It evaluates the time dependent electric charge distribution on a capacitive probe after application of a voltage step. The probe, shown schematically in Fig. 1, consists of a cylindrical metal stub, surrounded by a guard electrode, and a metal chuck that provides both the electrical back contact and mechanical support of the wafer to be measured. The stub is approached to the wafer surface until the distance equals about 1/10 of the thickness of the wafer. A precise horizontal xy stage serves to translate the wafer underneath the probe in order to generate a resistivity topogram.

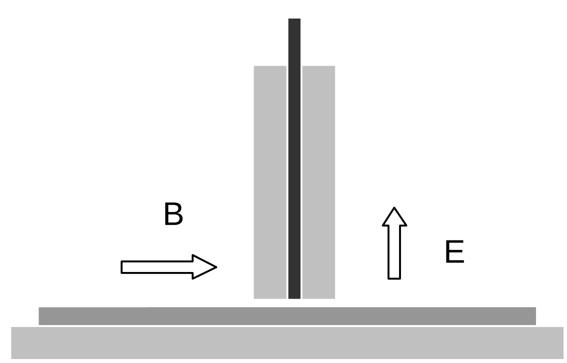

Fig 1. Schematic representation of the capacitive probe

The equivalent circuit of the arrangement, as shown in the insert of Fig. 2, consists of an air capacitor and a sample capacitor that contains the portion of the wafer material below the stub as a lossy dielectric medium. The finite resistivity of the wafer material accounts for the shunt resistor.

The exponential time dependence of the charge **Q(t)**, as shown in Fig. 2, allows to measure the relaxation constant τ and the charges **Q(0), Q(∞).** Using these quantities and the dielectric constant ε, the resistivity is calculated according to

$$\rho = \tau\, Q(0) / \varepsilon_0 \varepsilon\, Q(\infty) \qquad (1)$$

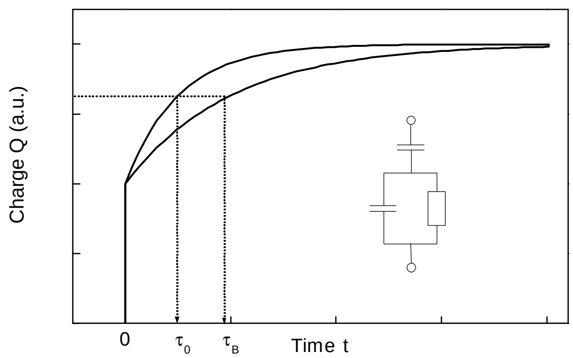

Fig. 2 Charge transients observed after application of a voltage step. The influence of the magnetic field B is indicated. The insert shows the equivalent circuit of the capacitive probe.

The capacitive evaluation avoids the necessity to cut samples from wafers and to prepare ohmic contacts. It is very fast (100 ms per data point), highly repeatable (better than 1 %, limited by sample temperature variations) and yields topographic ρ images of whole wafers with high lateral resolution (≤ 1mm). For these reasons, COREMA is considered superior to conventional contacting techniques, e.g. van der Pauw or linear four point probing.

The contactless measurement of the electron mobility μ relies on the magnetoconductance effect. Conventional Drude theory predicts that the conductance **σ(0)** measured without magnetic field is modified by the application of a finite magnetic field B according to

$$\sigma (B) = \sigma (0)\, [1 + (\mu B)^2]^{-1} \qquad (2)$$

The relative orientations of **B** and the electric field **E** in the sample capacitor are indicated in Fig. 1. The charge transfer transients, observed with and without applied magnetic field **B** are shown schematically in Fig.2, yielding respectively the time constants **τ(0)** and **τ(B).** By repeating the measurement at different magnetic fields, the data shown in Fig. 3 are obtained. The expected quadratic dependence is clearly indicated; exhibiting a standard deviation below 0.5% with respect to a quadratic fit. Hence, referring to eq. 1, the resistivity that determines the discharge of the sample capacitor must also depend quadratically on **B**, implying

$$\rho (B) = \rho(0)\, [1 + (\mu B)^2] \qquad (3)$$

Using eqs. 1 and 3, the mobility is evaluated according to

$$\mu = B\text{-}1\, ([\tau(B)/\tau(0)] - 1)\ ½ \qquad (4)$$

Comparative Hall and magnetoconductive measurements were done with samples cut from different ingots, covering a wide mobility range. The Hall data were obtained by the

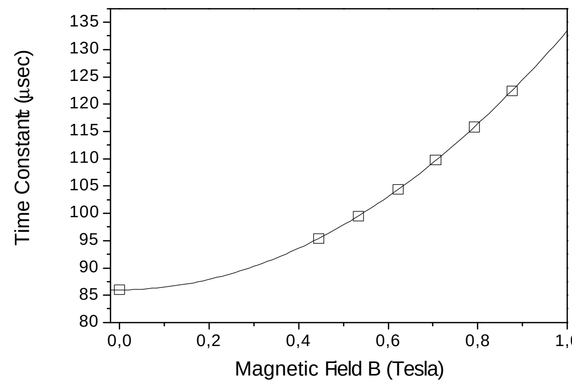

Fig. 3 Dependence of the charge transient time constant on the magnetic field, oriented horizontally, perpendicular to the electric field in the sample capacitor.

standard van der Pauw technique with 27mmx27mm samples, using a magnetic field B = 0,4357 T. The magnetoconductive data were obtained at B = 0.843 T with a 2.5 mm∅ capacitive probe, positioned in the center of the samples. The reproducibility of these measurements, with the samples removed and reinserted, is about 1%. The data are summarized and compared in Fig. 4.

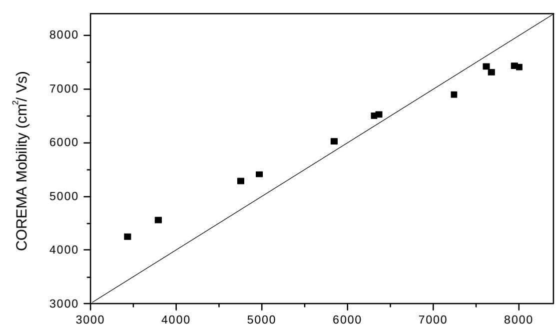

Fig. 4 Correlation of mobility data obtained by Hall and magnetoconductive measurement.

DISCUSSION

Two conclusions can immediately be drawn from the data in Fig. 4. First, a very satisfactory agreement of the absolute mobility values is obtained, giving confidence that magnetoconductance, as measured with the capacitive technique, is a reliable tool to determine mobility.

On the other hand, a systematic discrepancy appears to exist, such that, for low mobility, the magnetoconductive method yields about 20% higher values as compared to the Hall data. The difference decreases with increasing mobility and at high mobility the magnetoconductive data even appear to fall slightly below the Hall data.

These discrepancies may be due to a number of more or less significant reasons. For instance, as stated above, the measurements were done at significantly different magnetic fields. In addition, systematic differences of the mobility values as determined by the two measurement procedures are indeed expected and have been analysed theoretically [6]. Of course, such eventual systematic differences would not compromise the innovative approach, but would be included into the magnetoconductive evaluation routine, if Hall equivalent data were desired.

Both sets of data can be compared to mobility values derived from ionized impurity scattering theory. For most samples the shallow donor concentration is small and the net acceptor concentration is known. Because the net acceptors are compensated by the mid-gap donor EL2, the concentration of ionized impurities is about twice the net acceptor concentration. Application of Brooks-Herring formalism [7] allows to calculate the mobility reduction, compared to impurity-free material, as a function of acceptor concentration. For the lattice-limited mobility a value of 8000cm^2/Vs was assumed. As shown in Fig. 5, the agreement with COREMA data is excellent.

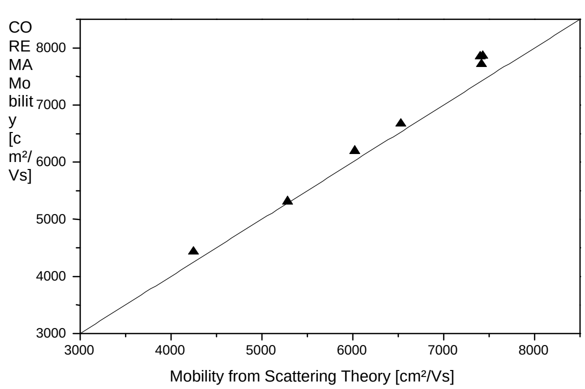

Fig.5 Comparison of mobility data obtained by magnetoconductive measurement with drift mobility obtained from ionized impurity scattering

In the resitivity range above 3x10^8 Ωcm increasing inhomogeneity of carrier concentration may cause a reduction of Hall mobility, whereas drift mobility is not influenced by inhomogeneities. A similar phenomenon is described in [8] for the resistivity range 10^3 Ωcm to 10^7 Ωcm. The COREMA measurement appears to be less influenced by carrier inhomogeneities than the Hall method.

A detailed investigation and discussion of these aspects is presently pursued, but is beyond the scope of this paper.

OUTLOOK

It is obvious that the contactless, COREMA-based mobility measurement offers a number of significant benefits, because the advantages of the capacitive resistivity measurement are essentially made available for the mobility evaluation. Hence, the procedure is fast, in particular because no sample preparation is required. Standard production wafers can be measured nondestructively, allowing to perform a reliable screening with any desired number of wafers per ingot without loss of material. While high resolution **μ** topograms may not be needed, an assessment of the mobility homogeneity across the wafer area, based on a customer-defined measurement plan, may easily be realized. Note, however, that the lowest mobility that can be evaluated is on the order of 1000 cm^2/Vs.

The data reported in Fig.4 have been obtained with a laboratory setup using a DC current magnet system. Such an apparatus would be disadvantageous for routine measure-ments in an industrial environment in regard of cost, volume and power consumption. To supply a strong magnetic field in the plane of large diameter wafers would require a very voluminous system and considerable magnetic field buildup

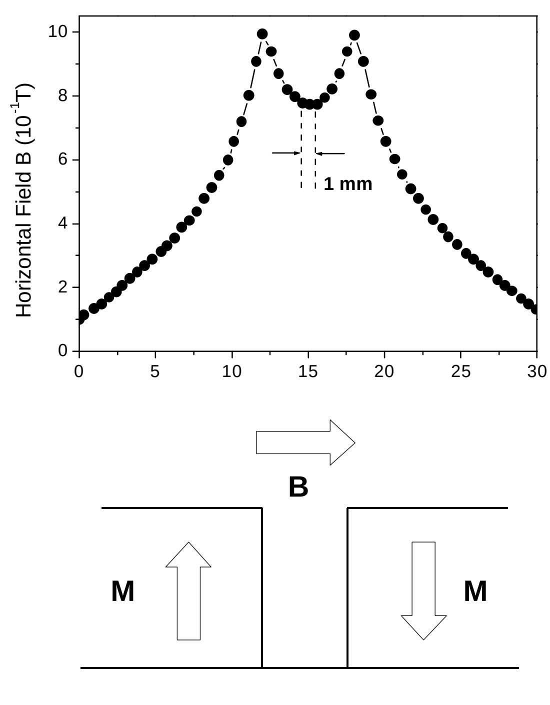

Fig. 6 Schematic representation of the permanent magnets supplying the horizontal magnetic field B. The upper part shows the calculated horizontal magnetic field in the plane 0.5 mm above the permanent magnets (data courtesy Vacuumschmelze).

time would elapse for each data point, because the mobility evaluation requires consecutive measurements with and without magnetic field.

We have, therefore, designed and tested a field generation arrangement with NdFeB permanent magnets, as indicated schematically in Fig. 6, lower part. Note that a strong horizontal magnetic field is required only within the measured material volume, which is located directly on top of the permanent magnets and is determined by the capacitive probe and the thickness of the wafer.

Fig. 6, upper part shows that at this location the horizontal field component exceeds 0.8 T. Within a disk with 1 mm ∅ and 0.5 mm thickness it is homogeneous to within a few %. Because it nevertheless declines rapidly in the vertical direction, the magnetic field is effectively removed from the measured volume by lowering the permanent magnet arrangement relative to the sample by about 30 mm. This allows to measure **τ(B)** and **τ (0)** consecutively in a very convenient way.

CONCLUSION

A superior and cost-saving technique to evaluate the mobility of semi-insulating GaAs and InP wafers has been demonstrated. Excellent reproducibility and satisfactory correlation with conventional Hall data has been obtained. The agreement with ionized impurity scattering theory is most convincing. An application oriented system design using an arrangement of permanent magnets is described.

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ACRONYMS

COREMA	Contactless Resistivity Mapping
TDCM	Time Domain Charge Measurement

