High Magnetic Field Transport in II–VI Heterostructures

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In the present work we report the results of magneto-transport measurements on some Hg–based II–VI semiconductor epitaxial layers grown by molecular beam epitaxy. The transport measurement were carried out at temperatures in the range 0.4 - 4.2 K in magnetic fields up to 10.0 T. Further, we point out the necessity of using multicarrier models for data interpretation and show finally some Shubnikov-de-Haas results on samples with high mobility carriers.

1 Introduction

The family of II–VI semiconductors includes materials with a wide range of properties (i.e. band gap, effective mass, etc.). On the one hand there are the Hg-based materials, which are semimetals, and on the other hand there the Zn-based materials with room temperature band gaps as large as 3.8 eV. Due to this large range of band gaps, the II–VI compound semiconductors are quite interesting for potential commercial applications and fundamental research. The use molecular beam epitaxy (MBE)to grow epitaxial layers of these materials has been recently widely employed in an effort to improve the the properties of these materials. Due to the low growth temperature during the MBE growth process, it is hoped that better control of the electrical properties can be obtained. Earlier growth techniques, which typically used higher growth temperatures, have been frustrated due to "self–compensation" effects. This has meant that reliable substitutional doping these materials has not been readibly achievable. Much of the recent II–VI MBE effort has been focussed on the growth of the narrow gap material HgCdTe. This is due to the fact that HgCdTe is presently the material of choice in the fabrication of infrared focal–plane arrays.

Van der Pauw Hall transport measurements are often employed as an initial characterization technique on epitaxial samples, because these measurements can be done quite quickly and easily. The quality of the sample usually is then characterized by the measured mobility and carrier concentration at low temperatures.

In the past also Shubnikov–de–Haasoscillationshave been reported for II–VI samples [1]. We have observed Shubnikov–de–Haas oscillations on several of our samples, allowing us a deeper look at the properties of those samples.

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2 Single carrier model failure and mobility-conductivity analysis

In recent years most transport data of MBE grown II–VI–semiconductor layers and heterostructures was interpreted using a classical one–carrier model. As is commonly known the transport phenomena are described in terms of a carrier concentration n and usually a Hall mobility μ when using a single carrier model. These two parameters are obtained from the measured values of the specific resistivity $\rho_{xx}(B=0)$ and of the Hall coefficient $R_H(B)$ at one given value of B using the formulae

$$n = -\frac{1}{eR_H(B)} \quad (1)$$

$$\mu = -\frac{R_H(B)}{\rho_{xx}(0)}. \quad (2)$$

The results are normally plotted in the form of carrier concentration or mobility as a function of temperature (e.g. [7]). In the valid range of the single–carrier model n and μ should be independent of magnetic field. If this evaluation is done for different values of magnetic field the calculated parameters of most mercury–containing samples appear to be a function of field, in some samples one or even two changes from n-type to p-type or vice versa occur (see fig. 1).

This clearly shows that such a simple calculation method should not be used for those samples. For bulk samples of HgTe, multiple–carrier models using up to four different carrier types at low temperatures have been employed[4, 5, 6], where the parameters were determined by fitting. As an alternative method we use the mobility-conductivity-analysis instead of a multi–carrier fit [3].

The mobility-conductivity-analysis, which was described originally by Beck [2], uses a classical model based on a solution of the Boltzmann equation that allows conduction in multiple bands, energy dependent relaxation times and nonparabolic bands. Within this model the components of the conductivity tensor are expressed in terms of a conductivity density $s(\mu)$ in the following way

$$\sigma_{xx} = \int_{-\infty}^{\infty} \frac{s(\mu)d\mu}{1+\mu^2B^2} \quad (3)$$

$$\sigma_{xy} = \int_{-\infty}^{\infty} \frac{\mu B s(\mu)d\mu}{1+\mu^2B^2}. \quad (4)$$

In principle the conductivty density now can be calculated by reversing these transformations. Practically this reversing can be done only using a small (in our case 7) number of field values due to numerical diffculties and due to the fact that σ_{xx} and σ_{xy} are known only at a finite number of magnetic field

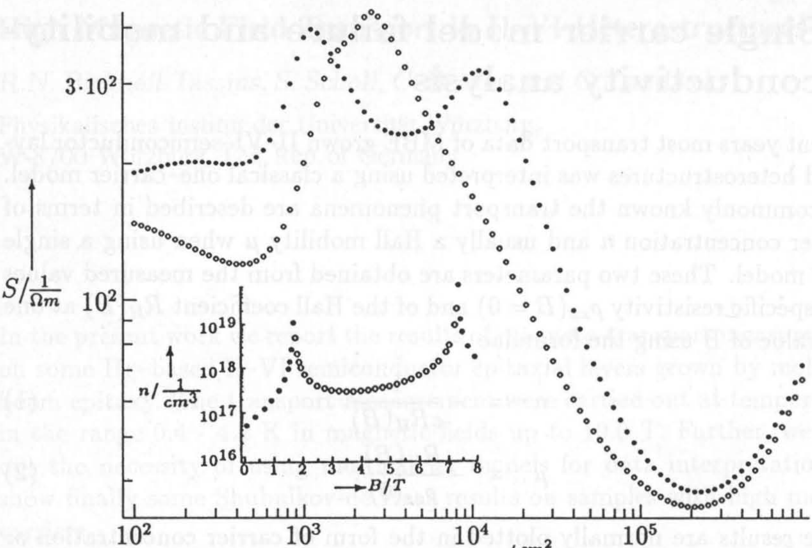

Figure 1: Mobility-conductivity-spectrum of a HgTe sample at 0.4 K, o holes, • electrons. Inset shows the same data evaluated in the single–carrier model (o p-type, • n-type).

values with a certain measurement error. As a consequence the calculation yields in general only an envelope $S(\mu)$, which can be interpreted as the maximum conductivity density at a given mobility that does not contradict the measured data. This envelope is still useful, because there are maxima at mobilities where real carriers in terms of the classical model exist. If quantum mechanical effects like magnetic freezeout occur, there may be artifact carrier types in the spectrum, also the data must be taken from field regions where no significant oscillations are visible. Therefore and also because of the possible effects of sample inhomogenities on van der Pauw measurements a cautious interpretation is required. Figure 1 shows the conductivity-mobility-spectrum for the sample with the two type changes. As you expect from the two changes, there are three types of carriers present.

3 Single layer samples showing Shubnikov–de–Haas oscillations

As already mentioned one parameter that is typically used to optimize the growth process is the mobility of the carriers present at low temperatures. To demonstrate that it is not always safe to regard the presence of high mobility carriers as a quality criterium we show the results on a $4\mu m$ thick

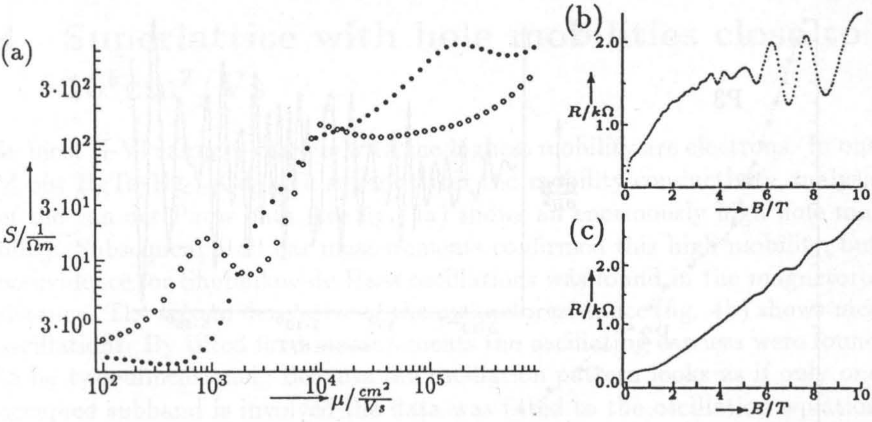

Figure 2: (a) Mobility-conductivity spectrum of a high mobility single layer HgCdTe sample (van der Pauw configuration), T = 0.4 K, ∘ holes, • electrons, the maxima close to $10^4 cm^2/Vs$ are due to magnetic freezeout.
(b) SdH oscillations measured on a Hall bar made from this sample, T = 0.4 K.
(c) Hall effect of this Hall bar, T = 0.4 K.

$Hg_{0.88}Cd_{0.12}Te$ layer. We have obtained similar results on HgTe epilayers. The mobility–conductivity analysis of measurements in van der Pauw geometry shows n–type carriers with a mobility high enough to expect Shubnikov–de–Haas oscillations (fig.2a).

Because the van der Pauw measurements show no evidence of oscillations a Hall bar was made from the sample. The results on this Hall bar show strong oscillations and some structure in the Hall effect that looks like Hall plateaus (fig. 2b,c). This indicates that van der Pauw measurements are useful to get some qualitative results, but for a more detailed characterization this method should not be employed.

The magnetoresistance at 45^o tilt angle between sample and magnetic field showed that all found periods changed approximately in the way one would expect for two–dimensional carriers.

For a more detailed analysis of the oscillation structure the second derivative of the resistance with respect to the field was recorded by field modulation (inset of fig. 3). The maxima in the second derivative were numbered with integers and plotted against inverse field. This plot shows three sections where the points are on a line (fig. 3).

From these results we conclude that the carriers responsible for the oscillation are two–dimensional carriers and that three subbands are occupied. The properties which can be estimated are listed in table 1. The concentrations listed there are not individual subband occupations at zero field, but the number of carriers responsible for each part of the oscillation. The step-

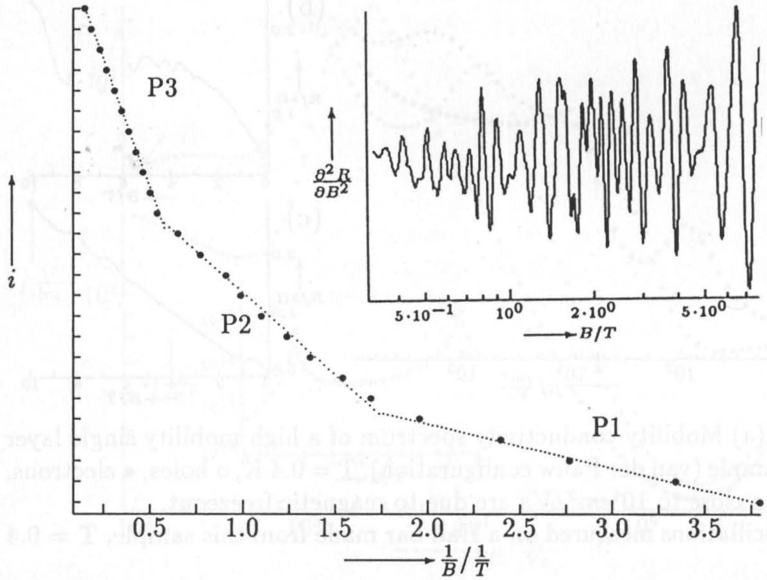

Figure 3: Number of oscillation maxima of the HgCdTe sample against inverse field, inset shows oscillation pattern in arbitrary units as functions of field, T = 1.5 K

Table 1: Parameters of the Shubnikov-de-Haas oscillations, the values preceeded by "≈" could be estimated only due to noise

Nummer	$P/\frac{1}{T}$	$\frac{m^*}{m_0}$	T_D/K	$n_{2D}/\frac{1}{cm^2}$
1	$(4.5 \pm 0.7)\cdot10^{-1}$	≈ 0.02	≈ 2	$(1.1 \pm 0.2)\cdot10^{11}$
2	$(1.3 \pm 0.3)\cdot10^{-1}$	≈ 0.02	≈ 2	$(3.7 \pm 0.7)\cdot10^{11}$
3	$(3.8 \pm 0.6)\cdot10^{-2}$	0.3 ± 0.2	—	$(1.3 \pm 0.2)\cdot10^{12}$

like structures in the Hall effect seem to be quantized Hall effect steps, but the measured resistance does not agree with the expected quantized values. This is probably due to conduction by additional nonoscillating low mobility carriers. A mobility-conductivity analysis performed on the low field part of these measurements where no oscillations are visible (B < 1 T), yields concentrations of the high mobility carriers that agree within the uncertainty of the evaluation with the Shubnikov-de-Haas results. Whether the carriers reside close to the surface of the sample or near the growth interface to the CdTe buffer will be a matter of further investigation of our samples. From other groups there are results which indicate that those carriers reside close to the buffer layer [13].

4 Superlattice with hole mobilities close to $10^5 cm^2/Vs$

In most II-VI samples carriers with the highest mobility are electrons. In one of our $HgTe/Hg_{0.11}Cd_{0.89}Te$ superlattices the mobility-conductivity analysis of the van der Pauw data (see fig. 4a) shows an enormously high hole mobility. Subsequent Hall bar measurements confirmed this high mobility, but no evidence for Shubnikov-de-Haas oscillations was found in the magnetoresistance. The second derivative of the magnetoresistance (fig. 4b) shows nice oscillations. By tilted field measurements the oscillating carriers were found to be two–dimensional. Because the oscillation pattern looks as if only one occupied subband is involved the data was fitted to the oscillation equation [1]

$$\frac{\Delta\rho}{\rho_0} = \sum_{R=1}^{\infty} \frac{5}{2}\left(\frac{RP}{2B}\right)^{1/2} \frac{\beta T m' \cos(R\pi m' g^*/2)}{\sinh(R\beta T m'/B)} e^{-R\beta T_D m'/B} \cos\left[2\pi\left(\frac{R}{PB} - \frac{1}{8} - R\gamma\right)\right], \tag{5}$$

but additionally the effect of the field modulation was included. This fit allowed the parameters listed in table 2 to be determined.

Table 2: Shubnikov-de-Haas parameters of the superlattice with high mobility holes

$P/\frac{1}{T}$	$\frac{m^*}{m_0}$	T_D/K	g^*	γ
0.127 ± 0.020	0.03 ± 0.01	12 ± 3	25 ± 5	0.18 ± 0.05

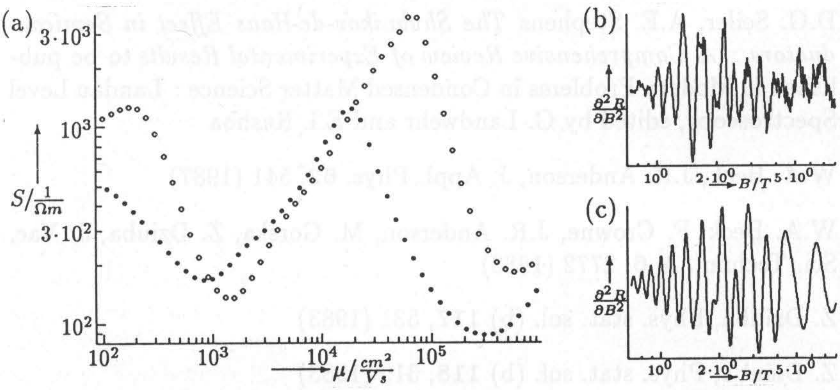

Figure 4: (a) Mobility-conductivity spectrum of superlattice with high mobility holes (van der Pauw method), T = 0.4 K.
(b) Second derivative of the magnetoresistance showing SdH oscillations, T = 1.5 K.
(c) Numeric simulation of the oscillation,
(b) and (c) show second derivative in arbitrary units versus field.

Out of these parameters the expected form of the oscillation has been calculated (fig. 4c), at least in the lower field region the agreement is quite good. In fields higher than 2 T there is some difference, probably due to the band structure.

5 Conclusion

We were able to demonstrate that a single carrier evaluation of transport data should not be used for semimetallic Hg–based samples and a multi–carrier–type model like the mobility–conductivity–analysis should be used instead. Moreover, we showed that detailed Hall bar measurements are essential for correct understanding of the conduction in Hg–based MBE-samples at low temperatures especially if the samples seem to contain high mobility carriers.

6 ACKNOWLEDGEMENTS

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