THEORY AND REALIZATION OF A TWO - LAYER HALL EFFECT MEASUREMENT CONCEPT FOR CHARACTERIZATION OF EPITAXIAL AND IMPLANTED LAYERS OF SiC

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ABSTRACT

Epitaxial and implanted layers are generally characterized by Hall effect measurements using a pn-junction as electrical insulation of the layer from the substrate. Due to defects, low doping concentrations or thin layers the resistivity of epitaxial or implanted layers is comparable to the resistivity of the pn-junction and the substrate. This results in inefficient electrical insulation between both regions. To be able to determine the properties of epitaxial or implanted layers even in the case of substantial leakage current we developed a two-layer Hall effect measurement concept. This concept is based on the conventional van der Pauw technique applied to the layer and the substrate separately. In addition the current-voltage characteristic of the pn-junction is measured and modeled in the analysis as an ohmic resistor.
This two-layer concept is applied to epitaxial grown SiC and the results are compared with conventional van der Pauw technique. In addition both techniques are compared with the results of capacitance-voltage (CV) measurements and secondary ion mass spectroscopy (SIMS).

INTRODUCTION

The importance of SiC as a material for high temperature and high power devices is steadily increasing. Among other things, this is accomplished by an improved doping control in both epitaxial crystal growth and in ion implantation processes. By this development the demands on the accuracy in techniques for characterization of doped layers is increased.
A powerful and well established technique for determining fundamental electrical transport properties is the measurement of the Hall effect. From this technique resistivity, free carrier concentration and carrier mobility can be deducted. Ionization energy and concentration of dopants governing the conductivity type, as well as the degree of compensation can be determined from the temperature dependence of the carrier concentration by a least squares fit of the neutrality equation to the experimental data. However, this Hall effect measurements are only accurate, if they are performed at homogeneously doped layers. To achieve this conditions when measuring epitaxial grown or implanted layers on a substrate, the use of semi-insulating substrates or the insulation by a pn-junction formed between the substrate and the measured layer are generally be sufficient. In the case of SiC, semi-insulating substrates do not yet commercially exist, and pn-junctions formed by ion implantation or epitaxial growth block high voltages within small areas, but they become leaky, when they are extended over large areas, which is the case in Hall effect measurements. One main reason for this leakage currents is a high concentration of crystal defects, e.g. micropipes.
We have developed a technique to cope with the influence of undesired currents through the substrate on the Hall effect results. Our method makes it possible to separate two layers, e.g. a substrate and an epitaxial layer, from each other. This is accomplished by an accurate measurement of the resistivity of the pn-junction, and subsequently by calculating the carrier concentration and mobility in the substrate and epitaxial layer separately.

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In this paper we present the theory of a two-layer Hall effect measurement concept. We show results from measurements on p- and n- doped epitaxial layers grown on 6H-SiC, and compare them with results obtained with the conventional van der Pauw technique, as well as SIMS and CV-measurements.

SIMULATION OF THE TWO-LAYER HALL EFFECT MEASUREMENT

In the conventional van der Pauw technique resistivity, carrier concentration and mobility are calculated for a single layer [1]. For the two-layer Hall effect concept these basic equations have to be extended by taking into account the interaction between the two layers. A detailed description of a possible equivalent circuit for this extension and the equations for calculating Hall coefficients and resistivities of the two layers are summarized in ref. [2]. In this paper we describe a method to simulate Hall effect measurements on two-layer pn-structures.

Assuming two homogeneously doped layers of different resistivity and opposite conductivity type, the free carrier concentration in each layer can be described by the neutrality equation. For the calculation of the neutrality equation values for the ionization energy and concentration of dopants, and for the compensation are needed. Knowing the carrier concentrations the Hall coefficients and the resistivities of the n- and the p-layer can then be calculated by using a Hall scattering factor of 1.0. For the calculation of the resistivity the mobilities of electrons and holes as a function of the temperature are described by a combination of the mobilities for phonon and impurity scattering mechanisms. Using the standard van der Pauw equations and knowing the thicknesses of the layers, the internal Hall voltages and the voltage drops during resistivity measurements can be derived for each layer separately.

If these independently modeled layers of opposite conductivity type are brought into contact, a pn-junction is formed between them. By keeping the voltage across the pn-junction well below its turn on voltage, the current-voltage characteristic of the pn-junction can be linear approximated and the pn-junction can be treated as an ohmic resistor. The parallel equivalent circuit obtained is then the basis for further calculations of current and voltage distributions in the composite structure. In the following it is assumed, that the current is applied only to one of the layers (e.g. to the epitaxially grown or implanted layer) to be able to compare the simulation results with results of conventional van der Pauw measurements on epitaxial layers. The pn-junction at the interface is assumed to be perfectly uniform.

EXPERIMENT

For Hall effect measurements samples were epitaxially grown on commercially available substrates in a horizontal reactor for vapor phase epitaxy in detail presented in ref. [3]. Silane and propane were used as growth precursors, while trimethylaluminium (TMAl) and nitrogen were used to achieve p- and n-type conductivity, respectively. The growth temperature was about 1600°C, the reactor pressure 800 mbar, and the growth rate 2.5 µm/h, with palladium diffused hydrogen as carrier gas.

Four ohmic contacts with a thickness of 100nm were formed both on the substrate and on the epitaxial layer by electron beam evaporation of either nickel or titanium followed by a subsequent anneal at 950°C. Standard van der Pauw Hall effect measurements were performed in a temperature range of 100K to 450K on two-layer structures consisting of a thin epitaxial layer on top of a substrate of opposite conductivity type. The van der Pauw technique was extended for measurements both at the substrate and at the epitaxial layer site. In addition the current-voltage characteristic and the resistance of the pn-junction was recorded.

The atomic concentration of dopants was measured with secondary ion mass spectroscopy (SIMS) using a CAMECA ims 4f instrument. The Al profiles were obtained with O_2^+ primary ion beam and detection of $^{27}Al^+$. Capacitance-voltage (CV) measurements on evaporated titanium Schottky contacts were used to determine the net doping concentration.

RESULTS AND DISCUSSION

Fig. 1 shows the Al concentration determined by different measurement techniques as a function of the Al content in the gas phase during growth. In the concentration range below $10^{18}cm^{-3}$ we found a good agreement of the net doping concentration determined by CV-measurements and the atomic concentration measured by SIMS, indicating an almost complete incorporation of Al on electrically active lattice sites.

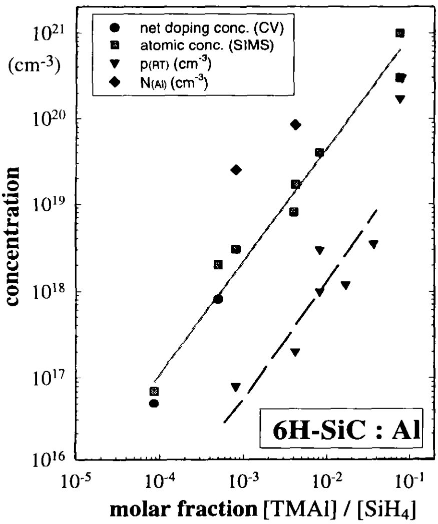

Fig.1 Al concentration measured by different electrical and atomic methods as a function of the Al content in the gas phase of the VPE reactor.

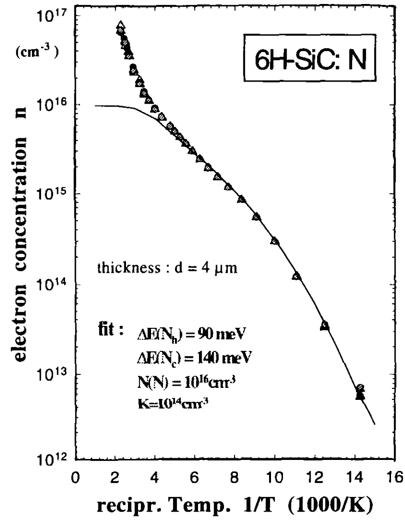

Fig.2 Temperature dependence of the electron concentration of an epitaxially grown n-type layer measured by the van der Pauw Hall effect method.

Compared to the linear dependence of the atomic Al concentration on the TMAl flow (SIMS) the Hall effect analysis gives a different result. Although the free hole concentration at room temperature in the Al-doped layers has the same dependency, resulting in a degree of ionization of around 1%, the Al doping concentration calculated by a fit of the neutrality equation to the experimental data is almost an order of magnitude higher than the atomic concentration. This discrepancy is less pronounced at higher Al concentrations, but is still too large to be explained by inaccurate material parameters (e.g. effective masses) or their temperature dependence.

In the case of N-doped n-type layers we found a similar behavior, where CV-measurements gave a net doping concentration a factor of 10 lower than the Hall effect analysis (fig. 2). To explain in this case the disagreement of CV and Hall effect by compensation is unrealistic as a degree of compensation of around 90% must be assumed.

In addition the Hall effect measurement on a n-layer, as shown in fig. 2, gives a temperature behavior at temperatures above 300K, which could be interpreted as an additional impurity with an ionization energy of about 250 meV. However, deep-level-transient-spectroscopy (DLTS) showed no indication of its presence.

The substantial difference in doping concentrations estimated from Hall effect measurements as compared to other standard characterization techniques could most probably be due to a low pn-junction resistivity. In order to investigate the influence of the resistance of the built-in pn-junction on the measured Hall coefficients and the corresponding free carrier concentrations by simulation, we assumed a two-layer structure consisting of a n-type thin layer on top of a thick p-type substrate. To make results of the simulation comparable with the experimental results (fig. 2) material parameters of 6H-SiC were used and a single impurity level for each layer was modeled by the neutrality equation. The ionization energy of N as n-type dopant and Al as p-type dopant in 6H-SiC were taken from ref. [4] and [5], and the doping concentrations were chosen in that way, that the results of the simulation is comparable to the result of the van der Pauw measurement. The compensation was assumed to be negligible. The parameters used for the simulation are summarized in tab. I.

Tab. I Material and impurity parameters used in the simulations of the two-layer Hall effect measurements

material: 6H-SiC			impurity		
layer	conductivity	eff. mass	symbol	ionization energy	concentration
1	n-type	$0.27\ m_0$	N	100 meV	$10^{16}\ cm^{-3}$
2	p-type	$1.0\ m_0$	Al	240 meV	$5 \cdot 10^{18}\ cm^{-3}$

Fig. 3 shows the dependence of the electron concentration in the n-layer and the hole concentration in the p-substrate on the pn-junction resistance for three different temperatures. The solid lines are the results of a simulation based on the two-layer concept, which represents a measurement on the combined structure. The dashed lines show for comparison the carrier concentrations calculated by the neutrality equation for each layer separately (i.e., at infinite pn-junction resistance).

For a temperature of 100K the model with separated layers and the combined model give the same result independent of the pn-junction resistance, indicating that at low temperatures the influence of the p-substrate is negligible due to its low hole concentration and therefore high resistivity. The conventional van der Pauw technique gives then accurate results.

At temperatures above room temperature the electron concentration calculated by the neutrality equation saturates as expected at the given N-concentration. The hole concentration in the substrate is strongly increasing, leading to a lower substrate resistance. The substrate is then influencing the measurement of the n-layer. At room temperature and a pn-junction resistance of 500Ω the influence of the substrate is expressed in an increase of the estimated electron concentration in the n-layer by almost a factor of 10. This factor is even higher when the temperature is increased to around 1000K and the hole concentration in the substrate has saturated at the level of complete ionization of the Al-acceptor.

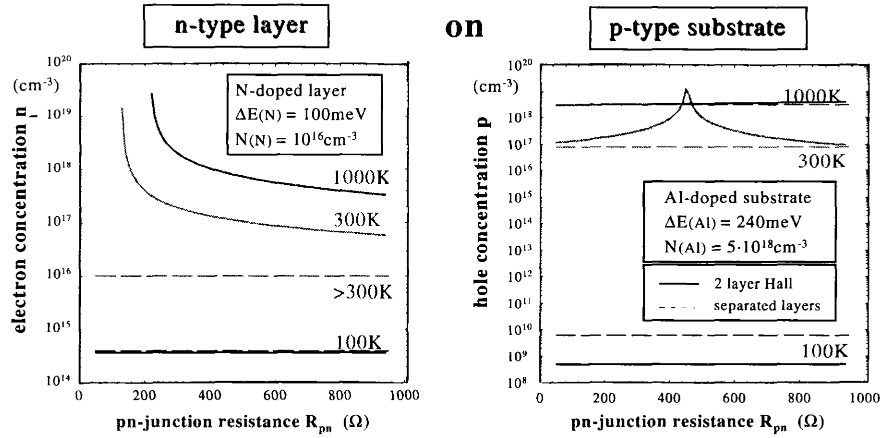

Fig.3 Calculated electron and hole concentrations of a two-layer structure consisting of a thin n-layer on a thick p-substrate as a function of the resistance of the pn-junction between the layers.

Performing a simulated temperature scan using the parameters of tab. I and assuming a linear temperature dependence of the resistance of the pn-junction, a qualitative comparison of the simulation with the real measurement (fig. 2) can be made. In fig. 4 the carrier concentrations are shown as a function of the temperature. The dashed curves are again representing the solution of the neutrality equation and the solid curves are the results of the two-layer Hall effect simulation. In the temperature range below 150K both calculations of the n-layer show the same concentration of free electrons. The concentration of holes in the substrate is much lower than the electron concentration. Therefore the resistance in the substrate is much higher than the n-layer resistance and no influence of the substrate on the electron concentration is seen. This changes, when the temperature is higher than 150K. The hole concentration in the substrate is steeply increasing and when it becomes comparable with the electron concentration in the n-layer the two-layer concept gives a value for the electron concentration which is higher than that estimated from the solution of the neutrality equation. The simulation of the two-layer structure above room temperature agrees quantitatively well with the experimental data on n-6H-SiC epitaxial layers. This clearly shows that the interpretation of the existence of an additional impurity could be falsified by the two-layer Hall effect simulations.

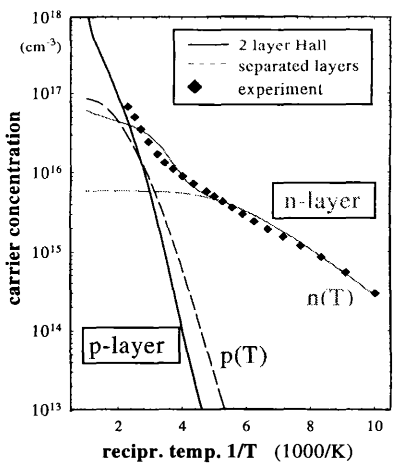

Fig.4 Simulated temperature dependence of the carrier concentrations in both the n- and p-layer compared to experimental data.

The two-layer Hall effect concept was realized in a computer controlled equipment. Room temperature measurements were carried out and are summarized in tab. II. The dopant concentration is calculated from the neutrality equation for comparison with SIMS and CV results, and with results from conventional Hall effect technique. Tab. II shows that the difference in doping concentration derived from standard Hall effect analysis for thin epitaxial or implanted layers on top of a thick substrate, and CV and SIMS measurements on the same samples can be resolved by taken into account the influence of a non perfect insulation on the layer transport properties as assumed in the presented two-layer Hall effect concept.

Tab. II Comparison of results from the two-layer Hall effect measurements with the standard van der Pauw method as well as with SIMS and CV results for Al- and N-doped Layers

		N doped layers	Al doped layers	
Measurement	concentration (cm^{-3})		low doping	high doping
two-layer Hall effect	free carriers (300K)	$1.6\cdot10^{15}$	$1.1\cdot10^{16}$	$5\cdot10^{16}$
	dopants	$2\cdot10^{15}$	$1.4\cdot10^{17}$	$7\cdot10^{18}$
standard Hall effect	free carriers (300K)	$1.2\cdot10^{16}$	$3.4\cdot10^{17}$	$7\cdot10^{17}$
	dopants	$2\cdot10^{16}$	$7\cdot10^{17}$	$5\cdot10^{20}$
CV	net doping	$2\cdot10^{15}$	$8\cdot10^{16}$	$6\cdot10^{18}$
SIMS	atomic	-	$1\cdot10^{17}$	$7\cdot10^{18}$

CONCLUSION

In conclusion, we have investigated epitaxially grown 6H-SiC films by Hall effect measurements. From a two-layer simulation it was shown, that the substantial leakage current over the pn-junction results in an overestimation of the carrier and impurity concentrations. This explains the difference between results from standard Hall effect measurements and other measurements of the impurity concentration. Furthermore artifacts in the conventional Hall effect measurements, which could be interpreted as additional impurities, can be explained by the two-layer concept as an influence of the substrate due to non-ideal pn-junction.

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