Estimation of Activation and Compensation Ratios in Al+ Ion Implanted 4H-SiC: Comparison of Two Methodologies

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Abstract. Activation and compensation ratios feature the electrical doping efficiency of a semiconductor material by ion implantation. The estimation of these ratios requires a quantitative evaluation of the density of the implanted dopant in substitutional position and of the density of the compensator centers after the mandatory post implantation annealing treatment. In the case of Al+ ion implanted 4H-SiC, it is a common habit to determine acceptor density, compensator density and acceptor thermal ionization energy by fitting the curve of the drift holes temperature dependence with the charge neutrality equation. However, this strategy could lead to ambiguous results. In fact, this study shows several cases of Al+ ion implanted 4H-SiC of interest for electronic device fabrication, where at least two sets of such fitting outputs can reproduce the same experimental curve within the uncertainty of the data. Provided that a model for the carrier transport could be set-up, the contemporaneous fits of the temperature dependence of drift hole density and of drift hole mobility is proposed to alleviate the uncertainty of the estimated acceptor density, compensator density and acceptor thermal ionization energy

Introduction

The electrical doping efficiency of a semiconductor material by ion implantation is qualified through the activation and compensation ratios, for which a quantitative evaluation of the implanted dopant density in substitutional position and of the compensator centers density are required, as well as the volume density of the as-implanted dopant. It is worthwhile to remember that the formers are measurable only after the mandatory post implantation annealing treatment.

In the case of Al+ ion implanted 4H-SiC, it has become a common habit to estimate acceptor density, compensator density and acceptor thermal ionization energy by fitting the temperature dependence of the measured drift carrier density in the ion-implanted layer by the charge neutrality equation. Nevertheless, the number of free parameters, that is three, may be large to accomplish the fitting procedure univocally. In the absence of peculiar features in the temperature trend of the carrier density, such as a clear change in the slope of this curve indicating the compensating impurity density [1], the existence of other constraints would help in increasing the reliability of the optimization of the fitting parameters, also called fitting outputs. Often the net acceptor density obtained from capacitance-voltage (C-V) measurements is the other constraint for consolidating the outputs of the carrier curves fitting, as examples see [2,3] for Al implanted layers and [4-5] for Al doped epi-layers. In this study we propose to use, as other constraint, the fitting of the temperature dependent mobility curve that is measured on the same van der Pauw (vdP) devices used for Hall effect measurements, i.e. for obtaining the temperature dependent carrier density curve. Moreover, the fact of using experimental curves that have been obtained on the same sample should hollow us to overcome the

issues/doubts arising when different samples as Schottky diodes or mercury probes for C-V measurements and vdP devices for Hall-effect measurements are used [5].

In case a model for the carrier transport could be set-up, the verification that the same set of free parameters (acceptor density, compensator density and acceptor thermal ionization energy) permits a good fit of the temperature dependence of the mobility data other than that of carrier density, may be an effective way to reduce the uncertainty on the output parameters. Examples of self-consistent fittings of the two set of data, applied to the case of low-doped p-type epitaxial 4H-SiC and Al^+ ion implanted 4H-SiC are in [6-7].

This study will show several Al^+ ion implanted 4H-SiC samples for which the fitting of the temperature dependence of the drift holes by using only the charge neutrality equation can be satisfied by several set of values for the free parameters with comparable agreement, so that the acceptor and compensator densities, and the acceptor ionization energy are not univocally determined. This drives us to think that for a reliable prevision of the electrical doping of 4H-SiC by Al ion implantation in devices fabrication, this method of analysis is not sufficient. Other constraints have to be taken into account together with the charge neutrality equation. We propose to use a model for fitting the temperature dependence of the drift holes mobility, if the sample doping is in a range for which a reliable model for carriers transport can be set-up.

Method, Results, and Discussion

All the samples of this study are from n-type homo-epitaxial off-axis <0001> 4H-SiC wafers with miss-cut angle of 4°. The doping level of the epi-layers is in the range $3\text{-}7\times10^{15}$ cm^{-3}. Moreover, all the samples have been processed and measured in house. Per each sample, Table 1 shows the more relevant processing parameters for the p-type doping by ion implantation. These parameters are Al implanted concentration, post implantation annealing temperature and annealing time. The studied ranges of ion implanted Al concentration is 6×10^{17} cm^{-3} – 6×10^{19} cm^{-3}, and those of post implantation annealing temperature and annealing time are 1600 – 1800 °C and 30 - 300 min, respectively. These ranges are of interest for optimizing the doping efficiency in the Al implanted p-type well, and well contact region, in n-channel 4H-SiC double implanted vertical MOSFETs.

The measurements of the sheet resistance and the Hall resistance coefficient of Al implanted layers were performed on square and four leaves vdP devices, in the temperature range 150-680 K. These data Hall curves were converted in drift ones by using the Hall factor of [4,6]. Hereafter we will use the terms holes curves and mobility curves to indicate their temperature dependence.

The charge neutrality equation was employed for the simulation of the holes curve and a mobility model for a non-degenerate electron gas for simulating the mobility curves. Such mobility model takes into account the usual scattering mechanisms (holes interaction with ionized and neutral impurities and with phonons) in the relaxation time approximation, with derivation of the energy-dependent total momentum relaxation time through the Mathiessen rule, as thoroughly explained in [6]. In this frame, the dominant electron-phonon interactions resulted to be the acoustic and non-optical ones via the correspondent deformation potential E_{ac} and E_{nop}, respectively.

Two fitting methodology approaches have been performed. One estimates the values of activation ratio, compensation ratio, and thermal ionization energy of the acceptors only by fitting the temperature dependence of the holes curves with the charge neutrality equation; we called this approach "p" fit. The other one estimated the same output parameters by fitting both holes and mobility curves; this was called "p-μ" fit. The uncertainties of fitting outputs are 3% for acceptor density, 10% for compensating center density, and 3% for acceptor ionization energy. Table 1 shows the "p" and "p-μ" fitting outputs values. The difference between "p" and "p-μ" values are larger than the output errors. This means that within the uncertainty of the experimental data, significantly different sets of acceptor density, compensator density and acceptor thermal ionization energy values, correspondent to different activation and compensation ratios, account for the same holes curve, with comparable accuracy. This open the issue on the choice of the values to use for a unique evaluation of the doping efficiency for the Al ion implantation process in 4H-SiC.

Table 1. Sample summary, ordered for decreasing Al as-implanted concentration. Per each sample, acceptors density, compensators density and value of acceptor ionization energy (E_A) as obtained by fitting methodologies "p" and "p-μ" (see text). Computed activation and compensation ratios.

sample label	Al implanted density [cm^{-3}]	ann. temp. [°C]	ann. time [min]	fitting method	acceptor density [cm^{-3}]	activation ratio [%]	compensator density [cm^{-3}]	compensation ratio [%]	E_A [meV]
220c-I7-vP1	6.0×10^{19}	1600	30	p	5.1×10^{19}	86	1.8×10^{19}	35	129
				p-μ	3.7×10^{19}	61	7.8×10^{17}	2	199
220c-I9-vP1	6.0×10^{19}	1600	30	p	4.8×10^{19}	79	1.5×10^{19}	31	136
				p-μ	3.6×10^{19}	59	1.0×10^{18}	3	200
350-C1-5A-vP3	1.0×10^{19}	1600	300	p	4.9×10^{18}	49	1.7×10^{18}	34	169
				p-μ	3.2×10^{18}	32	5.4×10^{17}	17	185
350-A3-1E-vP3	1.0×10^{19}	1600	30	p	6.0×10^{18}	60	2.9×10^{18}	48	169
				p-μ	3.1×10^{18}	31	8.7×10^{17}	28	185
354-Lb	9.6×10^{18}	1750	30	p	7.0×10^{18}	73	2.0×10^{18}	29	169
				p-μ	3.9×10^{18}	41	9.0×10^{17}	23	178
354-Mb	9.6×10^{18}	1800	30	p	9.2×10^{18}	96	2.2×10^{18}	24	166
				p-μ	4.5×10^{18}	47	8.8×10^{17}	20	175
350-C1-5A-vP2	3.0×10^{18}	1600	300	p	3.0×10^{18}	100	8.9×10^{17}	30	181
				p-μ	2.3×10^{18}	76	3.6×10^{17}	16	196
350-A3-1E-vP2	3.0×10^{18}	1600	30	p	2.9×10^{18}	96	9.3×10^{17}	32	189
				p-μ	2.3×10^{18}	77	6.2×10^{17}	27	194
220c-I9-vP2	6.0×10^{17}	1600	30	p	6.0×10^{17}	100	2.9×10^{17}	49	205
				p-μ	6.0×10^{17}	100	3.2×10^{17}	53	201

Some insights can be gained by looking at Figs. 1(a-b). These figures compare the results of the "p" (Fig. 1(a)) and "p-μ" (Fig. 1(b)) fits for sample 350-C1-5A-vP2 of Table 1. Similar graphs could be drawn for the other samples of Table 1. Fig. 1(a) shows an optimized fit of the Hall holes curve by "p" fit and, at the same time, the impossibility to fit the lower temperature side of the mobility curve using the same parameters. In this temperature range the Coulomb scattering is dominant and the fitting curve is directly influenced by the acceptor and compensator centers estimated by the "p" fit. None difficulty to find deformation potential Eac and Enop for fitting the high temperature side of the mobility curve where the phonon scattering is dominant. Differently, Fig. 1(b) shows that the set of output parameters obtained by methodology "p-μ" gives acceptable fits of both carrier and mobility curves within the uncertainty of the experimental curves over the whole range of temperature of measurement. This brings us to think that the doping efficiency estimated by the "p-μ" methodology may be more reliable.

By coming back to the values of Table 1, we can see that, except in the case of the lowest doped sample, the "p-μ" methodology brings to an estimation of lower activation ratios, lower compensation ratios and higher acceptor ionization energies.

Conclusions

This study shows that, within the uncertainty of the experimental data, two significantly different sets of acceptor density, compensator density and acceptor thermal ionization energy values account for the temperature dependent same holes data. This bring to the conclusion that the only fitting of the holes curve by the neutrality equation is not sufficient for a unique identification of the electrical doping efficiency in Al$^+$ ion implanted 4H-SiC. This, at least in the case of all the samples of this study that cover a quite large range of processing parameters of interest for the fabrication of 4H-SiC double implanted vertical MOSFETs.
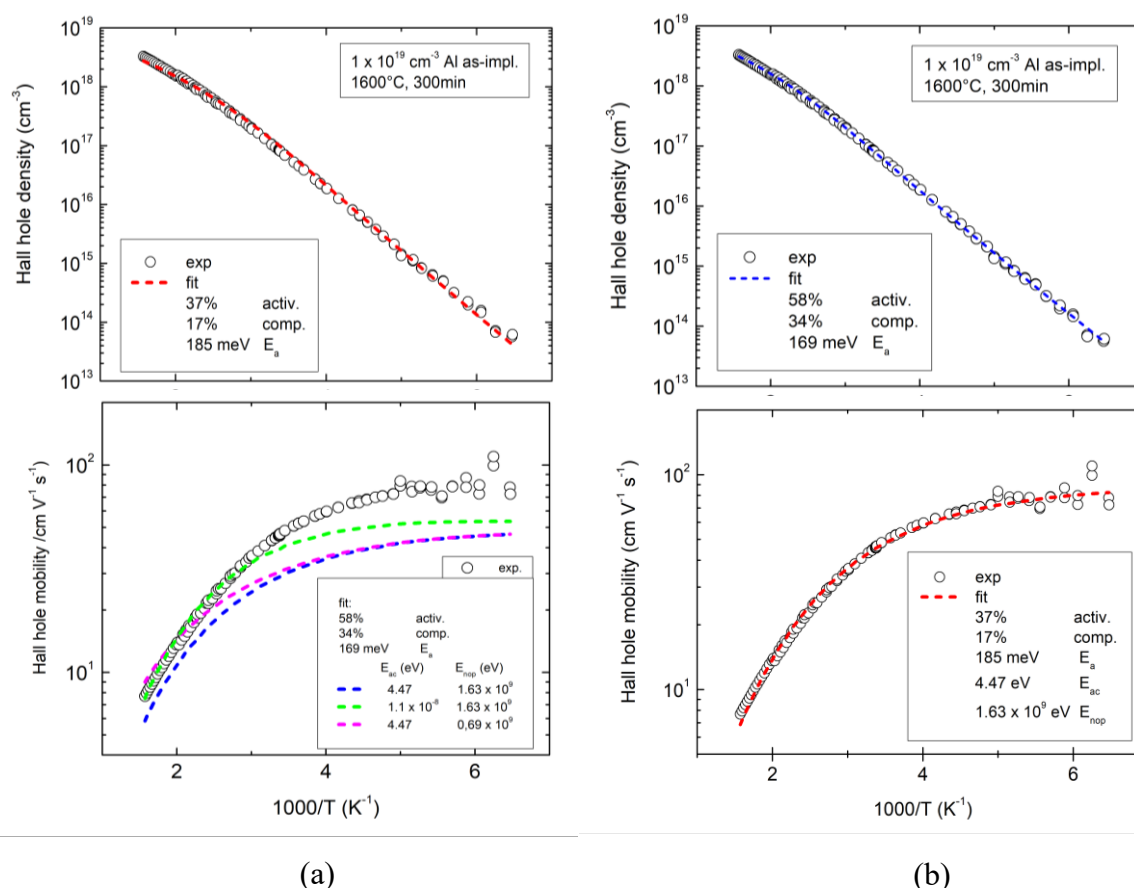
(a) (b)

Fig. 1. Application of the "p" and "p-µ" fitting methodologies to the same set of experimental curves: fitting output parameters are in the insets. (a) methodology "p" gives optimal fit of the carrier density curve but none fit of the mobility curve in the low temperature region, (b) methodology "p-µ" gives acceptable fits for both carrier density and mobility curves.

The issue of how to obtain a reliable and unique estimation of the electrical doping efficiency of the Al^+ ion implantation process in 4H-SiC, drive us to take into account other constraints in addition to the neutrality equation and the holes curves. An option, that we propose but others are possible, is the use of the holes mobility curves with an appropriate analytical model for carrier transport in 4H-SiC.

New insights on the thermodynamics of the electrical activation of ion implanted Al in 4H-SiC can be recognized only by using what we may shortly call a two constraints methodology for the quantitative analysis of the temperature dependence of both carriers and mobility data. Which makes the subject of our study timely.

Acknowledgments

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