ELECTRICAL CHARACTERIZATION OF THE FORWARD CURRENT-VOLTAGE OF AL IMPLANTED 4H-SIC PIN DIODES

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ABSTRACT

In this work,theforward current-voltagecharacteristics of n-type Al implanted 4H-SiC pin diodeshave been investigated experimentally and by mean of numerical simulations in the 298-378K temperature range. Our simulations were performed using proprietary simulations software. The model parameters to be calibrated in the simulation are the electron and hole minority carriers lifetimes.The measured forward I-V characteristics showed two differentbehaviour, the leaky behaved and well behaved diode. The later diodes were considered for simulation comparison.Employing temperature-dependent carrier lifetimes as a fitting parameter, the simulation indicates that drift layer and bulk carrier lifetime ranging from 10ns to 50ns. We achieved a good agreement between simulations and measured data. The measured and the simulated forward characteristics indicate an ideality factor of about1.3for the region 2.5V-2.78Vand 2.14 in the low injection region. Activation energies of about 1.61eV and 2.51eVare obtained respectively which are in good agreement with the expected values.

KEYWORDS: p-i-n diode, silicon carbide, silvaco, device simulation, lifetimes.

1 INTRODUCTION

Silicon carbide is a semiconductor material with interesting properties such as wide band gap and high breakdown field, the saturation electronic drift velocity and the thermal conductivity. As a consequence, SiC devices can perform under high-temperature, high-power, and/or high-radiation conditions in which conventional (i.e. narrow band gap) semiconductors cannot adequately perform[1-3]. Its ability to function under such extreme conditions is expected to enable significant improvements to a far ranging variety of applications and systems.

However, since this is a relatively new technology, more work must be performed to ascertain the detailed physics and real design benefits that can be obtained by developing even these simple 4H-SiC devices. To this extent, little research has been performed that combines detailed numerical device modeling with actual experiments. We help to fill this gap by using a drift-diffusion based simulator for 4H-SiC pin diodes. We then coordinate the combined use of the device simulator and experiments to extract key physical parameters, including temperature dependent lifetime, whichhelps to quantify the attributes of 4H-SiC device behavior.

In this paper,measurement and simulation of forward current-voltage characteristicson Alimplanted n-type for 4H SiC pin diodes were investigatedin the range of 298K-378K.Thesimulation was carried out using Silvaco’s ATLAS software[4],basedon the stationary drift-diffusion model including a model for incomplete ionization of the dopants. Physically based models for Auger recombination and Shockley-Read-Hall recombination are used as well. For the mobility model the empirical relation of Caughey-Thomas is used. Thus, temperature dependent electrical measurements are also employed to differentiate the various current transport mechanisms for the diodes. It will be shown that, depending on the temperature, 4H-SiC pin diodes could have various lifetimes, which is used as fitting parameters.

2 DEVICE STRUCTURE

The devices investigated are 4H-SiC p-i-n diodes.The layer structure consists, from bottom to top, of three parts: an ideal 300-μm n+ 4H-SiC substrate with doping concentration of 1019 cm-3, an n- epilayer with a thickness of 4.8 μm with a doping level greater than 3.5 1015 cm−3 and p+ anode regions were realized by Aluminum implant to obtain a SIMS peak value of 6x1019 cm-3 onto 5μm-thick and 3x1015 cm-3-doped epilayer,with an active area of 9.62x10-4cm-2. A schematic cross-section of the diode structure and the net doping profile are displayed in Figure1.

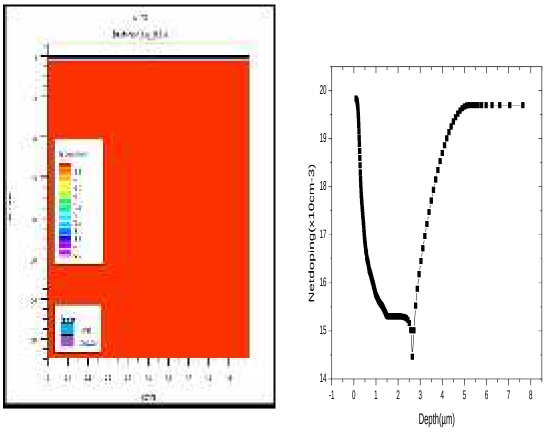

Figure 1:* *Schematic of 4H-SiC PiN diode, showing the cross-section and doping profile.

Implanted aluminum showed aplateau aluminum concentration of 6.1019 cm-3 located at the surface with a profile edge located at 0.2 µm and a profile tile crossing the n-type epilayer doping at1.35 µm. A high temperature annealing is usually necessary to reduce the damage caused by high-energy ions during implantation[5].The post implantation annealing is performed around 1873K for 30 min in an induction furnace with Ar ambient. Deposition of Ti/Al and Ni on P+ implanted region and n+ back surface of the wafer,respectively to insure the ohmic contacts.

3 SIMULATION MODELS

A 2D physically based numerical simulation silvaco package is used [4].The simulator is designed to design device structure and solves three-coupled non-linear partial differential semiconductor physics equations, where the charge transport equations are governed, in which physical models were incorporated in the simulator such as bandgap, mobility, carrier lifetime, incomplete ionization, impact ionization and Shockley-Read-Hall (SRH). The most important physical models employed in the numerical simulations are described as follows.

3.1 Band gap models

Since no data exist for 4H-SiC bandgap temperature dependence, it is supposed that 4H-SiC has the same one of 6H-SiC, as the following Eq.[6].

$$E_g(T)(eV) = E_{g,0} + dE_{g,0} - \frac{\alpha T^2}{\beta + T} \tag{1}$$

Where dEg0 is a band gap correction term. It is used together with an appropriate BGN model,α=3.3x10-4and β=0are material parameters and T is the lattice temperature in Kelvin.

3.2 Mobility models

The low-electric-field mobility is modelled by theCaughey–Thomas equation [7]:

$$\mu_v^{low} = \mu_{0v}^{\min\left(\frac{T}{300}\right)^{\alpha_v}} + \frac{\mu_{0v}^{\max\left(\frac{T}{300}\right)^{\beta_v}} - \mu_{0v}^{\min\left(\frac{T}{300}\right)^{\alpha_v}}}{1 + \left(\frac{N}{N_v^{crit}}\right)^{\delta_v}\left(\frac{T}{300}\right)^{\gamma_v}} \tag{2}$$

Table 1:* *Mobility parameters used in the simulations. Data taken from [4].

	μ_{0v}^{max} cm^2 /v.s	μ_{0v}^{min} cm^2/ v.s	N_v^{crit} cm^{-3}	α_v	β_v	δ_v	γ_v
n	950	40	2.00x10^{17}	-0.5	-2.40	0.76	-0.76
p	124	15.9	1.76x10^{17}	-0.5	-2.15	0.34	-0.34

3.3 Incomplete ionisation

In a SiC diode at room temperature and depending on the doping concentration, not all doping atoms are completely ionized, as it is the case for Si structures.

This is due to the wide bandgap of SiC compared to Si.

The carrier concentration N$^+$D, A$^{\text{(i.e. the number of ionized donorsor acceptors)}}$ can be calculated with the following equations [8].

$$N_D^+ = \frac{N_D}{1 + g_c\left[\frac{E_{Fn} - E_D}{kT}\right]} \tag{3}$$

$$N_A^+ = \frac{N_A}{1 + g_v\left[\frac{E_{Fn} - E_A}{kT}\right]} \tag{4}$$

Where gc and gvare the spin degeneracy (in this case 2 for donors and 4 for acceptors), NDand NAare the donor and acceptor impurities concentration, EDand EA are the donor and acceptor energy levels respectively, whereas EFnand EFprepresents the quasi-Fermi levels.

$\Delta E_D = 0.065\ eV$

$\Delta E_A =$ *0.191 eV*

3.4 Carrier lifetimes

TheShockley-Read-Hall (SRH) recombination rate is determined by the following formula [9].

$$R_{SRH} = \frac{np - n_i^2}{\tau_p\left(n + n_i \exp\left[\frac{E_t - E_i}{kT}\right]\right) + \tau_n\left(p + n_i \exp\left[-\frac{E_t - E_i}{kT}\right]\right)} \tag{5}$$

Where RSRH is SRH recombination rate, n and p are electron and hole densities, respectively, ni is the intrinsic carrier density, Et is the energy level of the recombination centers, τn and τp are electron and hole lifetimes, respectively, which are dependent on the doping level and the temperature.

The SRH carrier lifetimes in the above equation are modelled as functions of doping by the Scharfetter relation:

$$\tau_{n,p} = \frac{\tau_{n,p0}\left(\frac{T}{300}\right)^{\alpha}}{1+\left(\frac{N_i}{N_n^{SRH}}\right)^{\gamma}} \tag{6}$$

Where Ni is the total concentration of ionized impurities and τn0 is the electron lifetime in the material without impurities at 300 K.We found, the parameter set τn0=10 ns, N_n^{SRH}=2×1018cm-3, α=1.72 andγ=1.9 [10]. In the simulations, τn=5τpis assumed.

3.5 Impact ionisation

The acceleration of free carriers within a high electric field finally results in generating free carriers by impact ionization.The generation rate of electron–hole pairs due to impactionization is modelled according to Selberherr [11].

$$\alpha_{n,p} = a_{n,p} exp\left[\left(-\frac{b_{n,p}}{E}\right)^{\beta_{n,p}}\right] \tag{7}$$

Table 2 : Parameters of the electron- and hole-impact ionization coefficients of 4H-SiC. [12-13].

Parameter	(0001)	$(11\bar{2}0)$
a_n (cm^{-1})	1.76x10^8	2.10x10^7
b_n(v/cm)	3.30x10^7	1.70x10^7
a_p(cm^{-1})	2.41x10^8	2.96x10^7
b_p (v/cm)	2.50x10^7	1.60x10^7
β_n	1	1
βp	1	1

4 RESULTS AND DISCUSSION

The current-voltage measurement were realised on a HP4155 Semiconductor Characterization System curve tracer using 2-probes in Kelvin mode at different operating temperature.Over three identical diodes were measured and characterized with this technique, providing information on device performance.There were two diodes selected for I-V-T characterization for their best behaviour.Figure.2 shows the measured forward I-V characteristics on a logarithmic scale of The 3identical p-i-n diodes (D2A, D2E, and D2G).The I-Vcharacteristics of well-behaved diodesD2E and D2A and leaky diodeD2G are compared.The well behaved diodes D2E and D2A are characterized by a sharp turn-on at a relatively high "threshold" voltage, and the current is dominated by carrier diffusion in a region (d) and recombination in a region (c). The diffusion and recombination current mechanisms produce a quick rise in slope, which is a characteristic of high quality, low resistance, and efficient operation.Conversely the diode conducts considerable current at much lower voltages in regions (b), which is characteristic of conduction through tunnelling like leakage paths. This excess current can be considered as a 'leak' path or shunt connected in parallel with the (ideal) principal p-i-n junction.

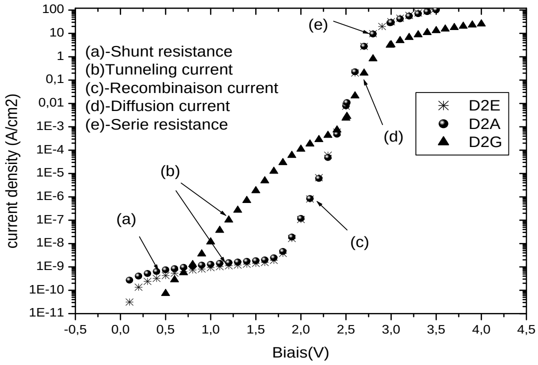

Figure 2: Measured forward characteristics of 4H-SiC of 3 diodes at 298K.

In many cases, such a shunt has nonlinear characteristics, i.e. represents barrier (e.g. characteristics D2G in Fig.2) .This behaviour can be attributed to the existence of defects in the active region such as screw dislocation, basal dislocation and threading edge dislocation [14].Fig.2 also shows the effect of series resistance, Rs, at voltages greater than ~2.70 V as shown in region (e). In this region, the forward voltage drop due to IRs becomes comparable to the applied voltage for the diodes D2A and D2E while the diode D2G exhibit high Rs. The Series resistance Rs is an important parameter thatinfluences the electrical characteristics so were by plotting the determined from region (e)of Fig.2 where at high current, the plot becomes flat and is assumed to be dominated entirely by the Rs. Rs is extracted by plottingI(dV/dI)versus I above is made and point where this curve saturates to a steady minimum value.

Thei-vcharacteristics of the well-behaved diodes D2A and D2E were selected in order to fit the simulation results. The recombination and diffusion dominated part of the forward biased pin-diode I-V characteristics are well suited as references for parameter evaluation and calibration because several possible sources of error can be excluded.Figure.3showthe simulated forward characteristics of diodes D2A and D2E for different carrier lifetimes adjusted to the measured current at T=298K in the range of 0V to 3.5V. The fitting parameter of carrier lifetime of 10ns is obtained for bias 1.8V to 2.7V which corresponds to the recombination and diffusion regions whereas all of them coincide in the series regions at current density of 100 A/cm2.The simulated and the measured characteristics are shown in figure.4.The thermal behavior of the 4H-SiC pin diodes in all temperatures seems to be the same, the conduction is purely unipolar due to a positive temperature coefficient and a lack of conductivity modulation in the drift region.The typical exponential region was observed, and it is the most useful for extracting the electrical parameters for the pin diodes.

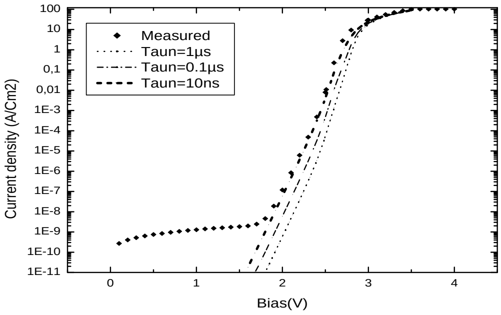

Figure 3: Measured and simulated forward characteristics of diodes D2A at 298K for variouscarriers'lifetimes.

The forward J-V characteristics at different temperatures (J-V-T) from 298K up to 378K were also simulated. The typical I-V-T characteristic of a diode is shown in Figure.4. The ideality factor, n, was extracted to be 1.3 between 2.5V and 2.8Vat different temperatures, betweenthese tendencies can also be seen when plotting the differential ideality factor.

$$n = q/(k_1 B\,T)\ \ 1/((d(\ln(I))\ /\ dt) \qquad (8)$$

This indicates that Shockley–Read–Hall recombination is the dominant mechanism in the conduction.The activation energy, Ea=1.61 eV, is obtained from an Arrhenius plot of ln(J0) versus 1000/T using the best linear fit to the expression J0 ∝T5/2exp(–EA/kT)[15]. Indeed, above 2.78V, the differential resistance measured is 3.4 mΩcm2compared to the estimated epilayer, substrate, and contact resistivity of 2.5 mΩcm2isobtained as follows.

$$R = 2R_c + R_{bulk} = 2R_c + \frac{d}{qN\mu_n S} \qquad (9)$$

Here, Rbulk is the semiconductor bulk resistance, d is distance between contacts, S area of contacts, µn the electron mobility and N the electron density.

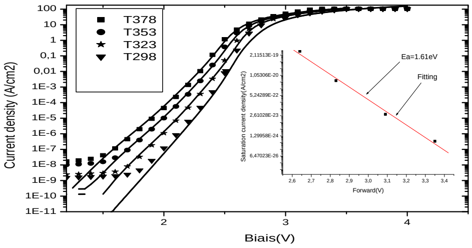

Figure 4: I−V characteristics (solid lines) for various temperature modeled by Silvaco device simulator tool.

The corresponding experimental curves (dotted lines) are also presented for reference of diode D2A.

5 CONCLUSION

Electrical characteristics of Al implanted 4H-SiC pin diodes have been presented. Measured of three identical devices, 2were found to be well-behaved exhibiting a minimum amount of tunneling current.Onewas classified as very poor, where recombination and tunneling were the dominant current processes at all voltages.For well-behaved diodes,forward I-V-T data showed current conduction due totunneling below 1.7 V, recombination between 1.7 and 2.5 V, and diffusion processes above2.5 V.

Series resistance was found to be a limiting factor around 2.9 V. Recombinationcurrents yielded an activation energy of 1.53 eV and an ideality factorin the range of 2.02-2.12 compared to the ideal activation energy of 1.63 eV with ideality factor of 2.The recombination and diffusion-dominated forward characteristics of the two well behaved pin-diodes have been also simulatedwithin a large temperature range with excellent agreement to measured data using a single material parameter, by adjusting the technology-dependent SRH minority carrier lifetimes, a value of 10ns was obtained.

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