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AUGER RECOMBINATION IN HEAVILY-DOPED p+ SILICON

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ABSTRACT

Minority carrier mobilities and Auger recombination in heavily doped p+ type silicon were determined using narrow base pin diodes as test structures. From transparent emitter theoretical and experimental analyses it was found that the minority electron mobility can be expressed as $\mu_n^p = \mu_n^n \exp(-\alpha \Delta Eg/kT)$ where $\alpha = 0.35$. It was found from the analysis of quasitransparent emitter diodes that a value of $3*10^{-32}$ cm^6 /s for the Auger coefficient Cp (a value three time lower then the previously reported one) better fits saturation current measurements.

1. INTRODUCTION

The intensive studies carried out in the last decade for the investigation of carrier transport in nonuniform semiconductors [1-4] and the requirement for highly accurate models of the silicon bipolar transistor [5-6] have helped the better understanding of heavy doping effects. The complex band structure of heavily doped silicon poses serious difficulties to the physical understanding of the transport and recombination of minority carriers. The problem becomes even more challenging if the doping level changes with position and the band structure itself becomes spatially dependent.

While the bandgap narrowing effect has been widely investigated during the past twenty years, minority carrier transport and recombination in heavily doped silicon has only recently attracted a major interest. Simultaneously, and partially as a consequence of the incomplete knowledge of the basic physics, the available experimental data regarding the relevant minority carrier transport parameters' values span one order of magnitude [7,8].

Although device modelling programs that solve the coupled semiconductor equations have been widely available for quite some time, only analytical solutions can provide physical intuition.

Even more so, only an analytical model facilitates the separation of various unknown heavy-doping-dependent parameters: bandgap narrowing, bandgap narrowing asymmetry factor (conduction and valence band offsets), minority carrier mobility and Auger recombination lifetime.

The recently deduced value of the Auger coefficient Cn in n+ silicon, determined from n+p junction solar cells measurements, are one order of magnitude lower than the originally reported values of Dziewior and Schmidt [9]. In contrast, Auger recombination in p+ silicon has been hardly investigated, the only data available in the literature being those reported in [9].

It is the purpose of this paper to investigate Auger recombination in heavily doped p+ type silicon using narrow base pin diodes as test structures.

Because two unknown parameters have to be determined, minority carrier mobility and Auger coefficient, their effect on the saturation current must be first singled out. Minority carrier mobilities will be derived from saturation current analyses and measurements of transparent emitter diodes (in which recombination can be neglected) while the Auger coefficient will be estimated from measurements on quasitransparent emitter diodes using the newly obtained values for minority carrier mobility.

The study is based on a recent model of the I-V and stored charge characteristics of narrow base pin diodes [10]. This model accounts for bandgap narrowing, degenerate statistics and Auger recombination in shallow emitters.

2. THE I-V CHARACTERISTIC OF NARROW BASE PIN DIODES

Experimental analyses performed on a wide range of narrow base pin diodes with base thickness w ranging from 0.5 to 2.5 μm and having transparent and quasitransparent emitters evidenced a wide current range (between several hundred μA and tens of mA) in which the ideality factor in the expression I = Is exp(qV/nkT-1) is rigurously 1(within 0.5%). In this range of bias currents the base operates under high injection level but its contribution to the I-V characteristic is not essential [11], because the minority carrier concentration is practically constant throughout this region. The I-V characteristic is governed by the physics of the p+ region alone. This region functions at low injection level with the carrier concentration damping down to its equilibrium value towards the surface.

If the emitter is considered quasitransparent and the following heavy doping effects are built-in:

(i) bandgap narrowing at moderate-to-high impurity doping [12];
(ii) impurity deionization via doping dependent acceptor level [13];
(iii) Fermi-Dirac statistics;
(iv) neglectable influence of degeneracy and the density of states in the conduction and valence bands;
(v) hopping conduction in band tails leading to several times lower minority carrier mobility values [14],

the expression of the saturation current can be cast as:

$$Is = \frac{q\, ni^2\, A \left\{ 1 + \int_{-xj}^{0} n^{\circ}(x) \left[Geff(-xj) - Geff(x) \right] dx / \tau n(x) \right\}}{Geff(-xj)} \qquad (1)$$

where:

$$Geff(y) = \int_{-y}^{0} Nv \exp\left[m(x)\right] dx \Big/ \left\{ Dn(x) \exp\left[\Delta Eg(x)/kT\right] \right\}$$

$1/\tau n = 1/\tau no + C_p p^2$ is the electron carrier lifetime in which the Auger recombination is included;

$n^{\circ}(x)$ is the minority electron concentration in the p+ region at thermal equilibrium and

$m(x) = [Ev(x)-Ef(x)]/kT$ is computed from the generalised charge neutrality equation in which an arbitrary impurity profile and position depedent acceptor level and bandgap narrowing are considered.

The well known Slootboom expression [12] is employed to describe the bandgap narrowing while the acceptor level variation with doping concentration is introduced by the empirical formula (adapted for p+ silicon) presented in [17].

If the emitter is transparent the integral term in the numerator of equation (1) vanishes.

It must be specified that the pn junction is located at x = 0 and the surface at -xj.

3. EXTRACTION OF MINORITY ELECTRON MOBILITIES FROM THE I-V CHARACTERISTIC OF TRANSPARENT EMITTER NARROW BASE PIN DIODES

For the accurate prediction of the saturation current Is in transparent emitter narrow base pin diodes the diffusion coefficient $D^p n$ of minority electrons must be precisely known. Recent experiments have revealed unequal majority and minority carrier mobilities $\mu^p n \neq \mu^n n$ [14,15].

We have adopted Fossum's minority hole model [14] to describe minority electron mobility. At room temperature this reduces, with a good approximation to:

$$\mu^p n = \mu^n n \exp(-\Delta E^{bt} c / kT) \qquad (2)$$

where $\Delta E^{bt} c$ (unknown) is the effective bandgap narrowing in the conduction band tails.

Although $\Delta E^{bt} c$ effectivily depicts bandgap shrinkage due to band-tail effects, it is our feeling that it may be regarded as a parameter similar to the conduction band offset in heterojunction theory. Consequently we have deemed it appropriate to extend the parallelism with the heterojunction theory and assume that, irrespective of doping level, $\Delta E^{bt} c$ is a constant fraction of the bandgap narrowing (as happens with ΔEc in the AlGaAs/GaAs system where Ec is a constant fraction of ΔEg for a wide range of mole fraction values (x = 0 - 0.4)).

The minority electron mobility model can now be recast as:

$$\mu_n^p = \mu_n^n \exp(-\alpha \Delta Eg/kT) \qquad (3)$$

where α is a constant to be determined from saturation current experiments.

Since the Auger coefficient in p+ silicon is not reliable, verification of the minority mobility model can only be achieved if recombination in the p+ emitter is rendered neglectable. To examine the range of doping profiles and emitter depths in which recombination may be neglected, we employ the quasitransparent emitter I-V model. It was shown by Alamo et al. [16] that the theoretical error between the transparent and quasitransparent emitter models can be a useful tool in the estimation of recombination effects.

It is obvious from equation (1) that the development of a reliable I-V model requires the accurate knowledge of minority mobility and Auger coefficient. The first will be determined from pin diode structures with very shallow emitters, while the second will be obtained from measurements on quasitransparent emitter diodes.

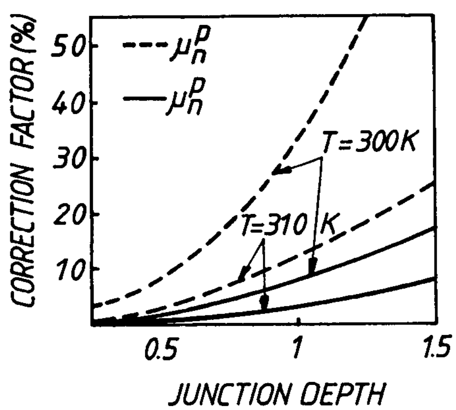

FIGURE 1
Comparison of transparent and quasitransparent emitter models as a function of junction depth, temperature and minority mobility model.

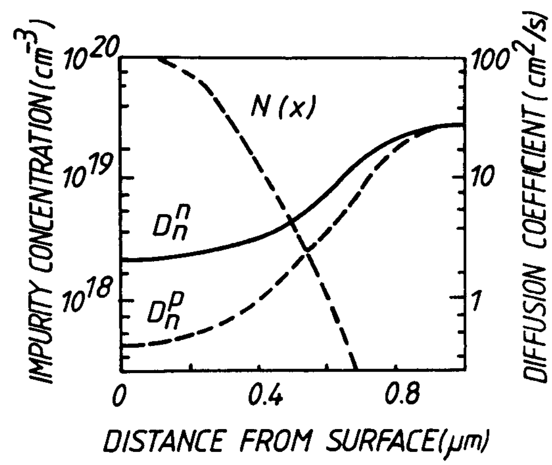

FIGURE 2
Minority electron diffusion coefficient as function of distance from the surface for α = 0.35 in a 1 μm emitter diode (dashed line).

Figure 1 presents theoretical results of the correction factor introduced by recombination in the emitter. The calculations have been performed using the currently accepted Auger coefficient, minority (α = 0.35) and majority mobility models.

These results clearly state that, for a safe and accurate derivation of the mobility model, diodes with emitter depths below 0.5 μm should be measured.

In order to determine the minority carrier mobility i.e. α, three types of transparent emitter diodes were manufactured using boron ion implantation. The three types of devices have the same junction depth $x_j = 0.4\ \mu m$ and different boron surface concentrations: $N_o = 1*10^{20}\ cm^{-3}$, $N_o = 5*10^{19}\ cm^{-3}$ and $N_o = 1*10^{19}\ cm^{-3}$, respectively. The base thickness is $2.5\ \mu m$. Measurements and calculation of saturation currents were performed at room temperature and at 314 K. It was found that $\alpha = 0.35$ realises the best fitting between the measured and calculated values of Is for all devices, at both temperatures. The measured and calculated values of Is for the three types of devices are presented in Table 1.

TABLE 1

No (cm^{-3})	T (K)	I_S (meas) (A)	I_S calc ($\alpha = 0.35$)
$1 \cdot 10^{20}$	298	$9.8 \cdot 10^{-16}$	$7 \cdot 10^{-16}$
$5 \cdot 10^{19}$	300	$1.53 \cdot 10^{-15}$	$1.46 \cdot 10^{-15}$
$1 \cdot 10^{19}$	298	$2.08 \cdot 10^{-15}$	$2.4 \cdot 10^{-15}$
$1 \cdot 10^{20}$	314	$0.89 \cdot 10^{-14}$	$0.71 \cdot 10^{-14}$
$5 \cdot 10^{19}$	314	$1.07 \cdot 10^{-14}$	$1.21 \cdot 10^{-14}$
$1 \cdot 10^{19}$	314	$2.25 \cdot 10^{-14}$	$2.80 \cdot 10^{-14}$

D = 110 µm

The newly obtained minority electron mobility profiles in a 1 µm junction diode are presented in figure 2 for $\alpha = 0.35$. The maximum error between theory and experiment is 35%.

The origin of this error is probably due to lack of precise knowledge of the actual doping profiles, especially in junction depth determination, a very difficult demand for shallow emitters. Even so, compared to other analytical models, the present theory offers a better match with Is measurements.

If heavy doping effects are neglected the saturation current is underestimated by nearly one order of magnitude; also, if majority carrier instead of minority carrier mobility is used, the computed saturation current is 4...5 times above the measured values.

4. AUGER COEFFICIENT EVALUATION

To obtain the Auger coefficient, a set of three currently available step recovery narrow base pin diodes with quasitransparent emitters were analysed. All devices were manufactured by boron diffusion (with $No = 1*10^{20}$ cm^{-3}) in a narrow epi-layer with $2.5*10^{14}$ cm^{-3} impurity concentration. For all devices the substrate was As-doped at $5*10^{19}$ cm^{-3}. The other profile parameters (junction depth, diameters, temperature) are presented in Table 2.

The table also includes the measured values of Is, (last column) and the computed ones using the transparent model and the quasi-transparent model (with $\alpha = 0.35$ and Auger coefficient $Cp = 9*10^{-32}$ cm^6 /s as given by Dziewior and Schmidt [9]).

TABLE 2

Diode type	X_j (µm)	D (µm)	T (K)	I_s^{trans} (A)	$I_s^{q\,trans}$ $Cp = 9\cdot10^{-32}\,cm^6/s$ (A)	$I_s^{q\,trans}$ $Cp = 3\ 10^{-32}\,cm^6/s$ (A)	I_s^{exp} (A)
S band SRD	1	194	298	$1.66\cdot10^{-16}$	$2.69\cdot10^{-16}$	$2.31\cdot10^{-16}$	$2.28\cdot10^{-16}$
X band SRD	1.2	76	297	$1.81\cdot10^{-17}$	$3.66\cdot10^{-17}$	$2.77\cdot10^{-17}$	$2.7\cdot10^{-17}$
K band SRD	1.5	20	294.5	$0.66\cdot10^{-18}$	$2.15\cdot10^{-18}$	$1.18\cdot10^{-18}$	$1.29\cdot10^{-18}$

The surprising feature revealed by the saturation current measurements is the fact that the error between theory and experiment is roughly the same for the two models, even for junction depths of 1.5 µm. The transparent model systematically yields values below the measured ones, while the quasitransparent model overestimates the saturation current.

One can see (Table 2) that the quasitransparent model gives results in excellent agreement with the experiment for all devices if a value $Cp = 3*10^{-32}$ cm^6 /s is employed. This value is three times lower than the currently accepted one.

5. CONCLUSION

The minority electron mobility and the Auger recombination coefficient Cp in p+ silicon were derived from narrow base pin diodes I-V characteristic modelling and saturation current measurements.

It was found that minority electron mobility can be expressed as:

$\mu_n^p = \mu_n^n \exp(-\alpha\Delta Eg/kT)$, where $\alpha = 0.35$, irrespective of temperature and the doping profile in the emitter. It appears that the exponential term in the mobility model plays in heavily-doped silicon a similar role with the conduction band offset, ΔEc, in nonuniform composition semiconductor systems. Further theoretical and experimental efforts are needed to support this assumption which may prove a major breakthrough in the development of a unified transport model in semiconductors. In such a formalism, heavily-doped silicon can be regarded as a graded heterojunction.

The Auger recombination coefficient was estimated to have a value three times lower than the currently accepted one (i.e. $Cp = 3*10^{-32}$ cm^6 /s). This confirms the trend of recent measurements which have also evidenced lower than originally published Cn values.

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