Simulation of Ion Irradiated Power Devices in ATLAS

J. Vobecky and P. Hazdra

Czech Technical University in Prague, Department of Microelectronics, Czech Republic

Introduction

About ten years of evolution was sufficient for ion irradiation technology to become a widely used tool for local carrier lifetime control in power devices. In 1994, the simulation of devices taking into account both the real defect profile resulting from ion irradiation and multi-level Shockley-Read-Hall model was published for the first time [1]. *ATLAS* has allowed simulation of transient traps since 1995 [2]. The last version of *ATLAS* (4.0) brought the possibility to account for arbitrary defect spatial distribution. So the development of ion irradiated devices using device simulation is now possible [3]. At present, any application of the simulator requires just a knowledge of the spatial distribution of the defects resulting from irradiation and electrical parameters of the related deep levels [4]. The practical application of this will be presented below for the case of power diode.

Background

Deep levels generated by ion irradiation affect the free-carrier thermal generation-recombination and hence the excess carrier lifetime. The thermal capture and emission of carriers through deep levels located within the bandgap is described in *ATLAS* by analytical model based on SRH statistics. In case of k independent single-charged acceptor- or donor-like levels the thermal components of the recombination rates R_n and R_p for electrons and holes, are respectively [1-3]:

$$R_n = \sum_{i=1}^{k} \left[K_{ni} \cdot N_{ti} \cdot (1-f_i) - G_{ni} \cdot N_{ti} \cdot f_i\right]$$

$$R_p = \sum_{i=1}^{k} \left[K_{pi} \cdot N_{ti} \cdot f_i - G_{pi} \cdot N_{ti} \cdot (1-f_i)\right]$$

where N_{ti} is the concentration of the i-th deep level and $G_{n(p)}$ and $K_{n(p)}$ are the i-th level emission and capture rates for electrons (holes). The electron occupancy f_i of the i-th deep level is calculated from the following balance equation

$$\frac{df_i}{dt} = K_{ni} \cdot (1-f_i) - G_{ni} \cdot f_i + G_{pi} \cdot (1-f_i) - K_{pi} \cdot f_i$$

The charge of traps $D_t=(p_t-n_t)$ influences the right-hand side of the Poisson equation

$$\varepsilon \nabla^2 \Psi = -q\,(p - n + N_D^+ - N_A^- + p_t - n_t)$$

Application of this model requires a detail knowledge of deep level parameters. The *ATLAS* command is

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doping trap ascii inf=… acceptor/donor  \
e.level=... sign=… sigp=… degen=…
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ATLAS also incorporates a model for transient trapping and de-trapping of carriers. For dynamic equilibrium $df_i/dt=0$ (DC analysis) CPU time is saved because the recombination rate R is unique and may be expressed explicitly by one equation in the following way

$$R_n = R_p = \sum_{i=1}^{k} N_{ti} \cdot \frac{n \cdot p \cdot K_{ni} \cdot K_{pi} - G_{ni} \cdot G_{pi}}{K_{ni} \cdot n + K_{pi} \cdot p + G_{ni} + G_{pi}}$$

Transition between the two states is automatic in *ATLAS.* There is available a second SRH model (`models srh`) which uses the static approximation even for transient analysis. In this case only a single G-R centre is considered and the equation above leads to the fairly well known formula

$$R_T = \frac{n \cdot p - n_i^2}{\tau_{p0} \cdot \left[n + n_i \cdot exp\left(\frac{E_t - E_i}{kT}\right)\right] + \tau_{n0} \cdot \left[p + n_i \cdot exp\left(\frac{E_i - E_t}{kT}\right)\right]}$$

where k is Boltzmann constant, T is the temperature, n_i is intrinsic concentration, E_i intrinsic Fermi-level, E_t trap level, $\tau_{n(p)0}=1/(\sigma_{n(p)} \cdot v_{n(p)} \cdot N_t)$ are electron and hole lifetimes, resp. It is worth reminding that this equation is true only for a single ideal G-R center ($R_n=R_p$) or dynamic equilibrium, (e.g. ON- or OFF-state).

Defining Trap Parameters

The device under consideration is a p^+pnn^+ power diode (2.5kV/100A) with length of 370μm between anode and cathode. The detailed device data may be found in [5]. In order to present the simulation capabilities of *ATLAS* the device under test was virtually irradiated by 10 and 18 MeV $^4He^{2+}$ ions with the dose of 5×10^9 cm^{-2} using the calibrated system for determination of defect distribution [1]. The parameters of deep levels created by penetrating ions were determined by means of the deep level transient spectroscopy (DLTS) and are summarized in Table 1 using the notation of *ATLAS.* Helium irradiation produces pure damage defects comprising five deep levels within the bandgap which are connected with different charge states of divacancy (E2, E3, H1), acceptor level of vacancy-oxygen VO pair (E1), and donor level of the carbon-vacancy-oxygen CVO complex (H2). The data received from measurements for level positions E_t

Acceptor-like traps					Donor-like traps				
Trap	E.LEVEL (eV)	sign (cm^2)	sigp (cm^2)	Identity	Trap	E.LEVEL (eV)	sign (cm^2)	sigp (cm^2)	Identity
E1	0.165	6×10^{-15}	3.4×10^{-13}	$VO^{(0/-)}$	H1	0.195	5.5×10^{-15}	5.1×10^{-16}	$V_2{}^{(0/+)}$
E2	0.23	1.5×10^{-15}	5.5×10^{-14}	$V_2{}^{(-/=)}$	H2	0.356	2.3×10^{-15}	3×10^{-16}	$COV^{(0/+)}$
E3	0.42	4.7×10^{-15}	2.8×10^{-14}	$V_2{}^{(0/-)}$					

Table 1. Deep levels in FZ n-type silicon irradiated by $^4He^{2+}$ ions.

(E.LEVEL) and electron capture cross-sections *sign* were completed by capture cross-sections for holes *sigp* presented in reference [4] for the same type of defects.

The influence of individual deep levels on electron lifetime is shown in Figure 1 for both the defect peak (x~180μm) and defect tail (50μm<x<150μm) regions of the 18 MeV irradiation (see Figure 2) using the general lifetime dependence on excess carrier concentration that reads

$$\tau_n = \frac{\Delta n}{R_n}$$

The thermal component of R_n was calculated from the first equation above for deep level parameters given in Table 1. Figure 1 enables one to compare the lifetime reduction in the defect peak with both the unirradiated region and tail part. Furthermore, $\tau(\Delta n)$ as a result of individual and all deep levels implies that only two levels are dominant.

The level E1 has the biggest impact on the lifetime decrease with increasing excess carrier concentration above 10^{14} cm^{-3} and determines the so-called high-level lifetime. The level E3 is counteracting, so it dominates in decreasing the lifetime below 10^{14} cm^{-3} . This is usually referred as a low-level lifetime. For the device under consideration, the E1 level is responsible not only for the magnitude of the DC forward voltage drop ($n > 10^{15}$ cm^{-3}), but also for the excess carrier recombination within the neutral n-base during the initial part of the turn-off. E3 brings mainly the desirable decrease of charge at the far end of reverse recovery ($n > 10^{15}$ cm^{-3}). Finally, the figure implies the fact that simulation with the two dominant levels (E1 and E3) gives the same results as with five ones (verified in simulations of reverse recovery). Since the influence of both the double-acceptor (E2) and single donor (H1) levels of divacancy is marginal, the defect can be approximated as a single acceptor E3. Therefore, a problem with inclusion of multiple-charged centers, which are not covered by the current *ATLAS* SRH model, is avoided.

Device Simulation

Figure 2 shows the excess carrier distribution $n + p$ of both the unirradiated and helium irradiated devices during the ON-state (100A@300K). Figure 3 shows the reverse recovery current and voltage waveforms to be simulated for dc reverse voltage -1000V and dI/dt=-1000A/μs starting from the conditions of Figure 2. The overall behavior of irradiated devices is influenced by position of the defect peak (ion energies) that was intentionally located in two places with different impact on

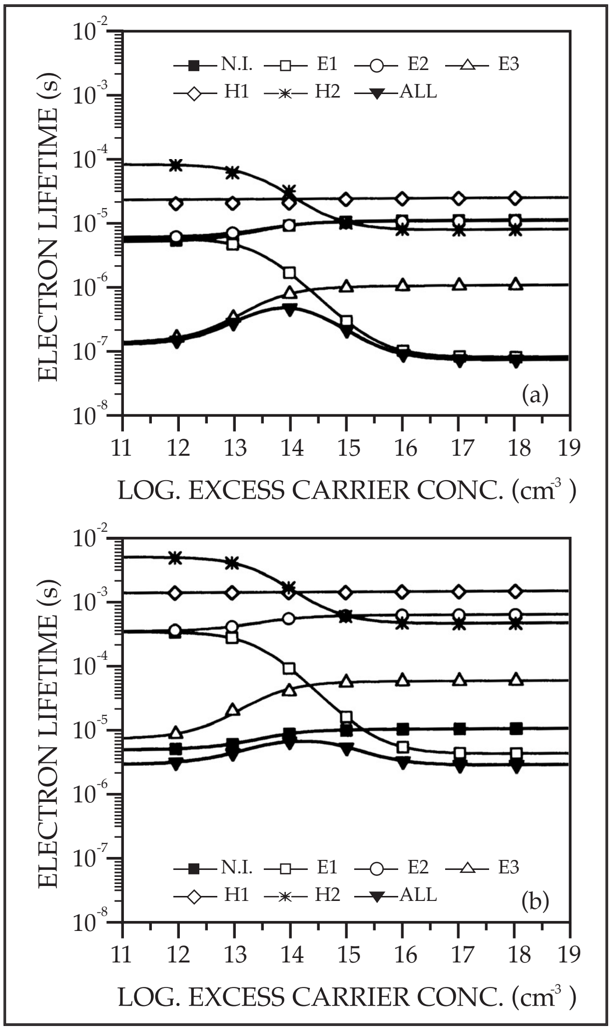

Figure 1. Electron lifetime at defect peak (top) and tail (bottom) vs. injection level ($\Delta n = \Delta p$, static approx., T = 300 K, N.I. = no irradiation, ALL=all levels accounted for)

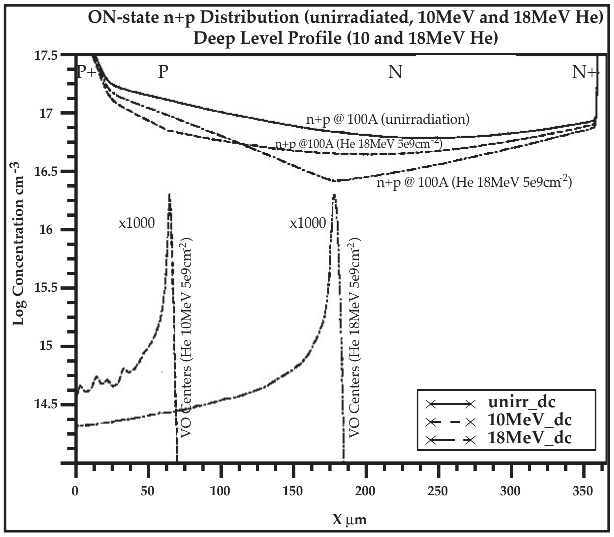

Figure 2. The profile of VO centers generated by 10 and 18 MeV He^{2+} $5x10^9$ cm^{-2} irradiation and ON-state sums of carrier distributions n+p for unirradiated and irradiated diode (I_f = 100A).

device parameters. The forward voltage drop V_F is 0.94, 0.98, and 1.032V @100A for unirradiated devices, 10MeV and 18MeV (dose: $5x10^9cm^{-2}$) irradiations, respectively. The gradual increase of V_F with defect peak distance from the anode is in agreement with experiment [5]. The influence of ion irradiation on dynamic behavior is more pronounced. While the unirradiated device shows oscillators, the 18MeV one is even worse. On the other hand, using 10MeV the defect peak placed within the n-base close to the anode softens the diode recovery in agreement with experiment [5]. As a result the removal of the oscillatory behavior takes place.

Conclusions

It was shown that *ATLAS* is capable of accurate simulation of ion irradiated power devices. The user should provide the electrical parameters of relevant deep levels and define trap models accordingly in the *ATLAS* syntax.

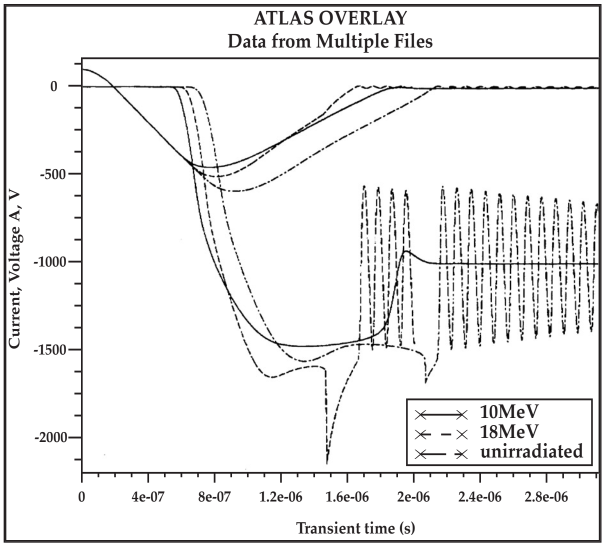

Figure 3. Current and voltage waveforms of the reverse recovery process (VRM= -1000V, dI/dt= -1000A/ms) for unirradiated and He irradiated diodes (10 and 18MeV@$5x10^9cm^{-2}$)

References

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