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Temperature Dependent Properties of Different Lifetime Killing Technologies on Example of Fast Power Diodes

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***Abstract* – Lifetime-controlled devices show different temperature behavior depending on the properties of induced recombination centers. The different recombination centers (Au-, Pt-doping, Electron and combined Electron and Helium irradiation) are compared for their influence on power device properties. DLTS and lifetime measurements of recombination center parameters over a wide temperature range explain the influence of lifetime killing on device behavior which is shown on the example of the measured temperature dependencies of the most important properties of fast freewheeling diodes.**

I. INTRODUCTION

Charge carrier lifetime adjustment is widely used for optimization of power device characteristics. By applying irradiation e.g. with electrons, protons or alpha particles it is possible to generate global or local lifetime profiles. With specific profiles, better device characteristics can be achieved, compared to the formerly used recombination centers gold or platinum [1]. Radiation generates different centers with different energy levels in the band gap. It was shown that donor-states of radiation-induced traps can generate dynamical electrical effects in semiconductor devices [2]. Further, the temperature dependency of device parameters is different when radiation-induced centers instead of platinum or gold are used [3]. Common simulation tools cannot predict this behavior because they only use a lifetime model and do not describe the levels of the recombination centers and their occupation probability. Since lifetime killing techniques nowadays are used for the optimization of a wide range of power devices [4-6], many efforts have been done in the past to estimate recombination center parameters for device simulation [7-14]. Based on an extended recombination model including full trap dynamics, simulations resulted in sufficient agreement with measured reverse recovery data but could not explain temperature dependency of the forward voltage [15]. Present improvements of simulation are based on more accurate lifetime measurements [22] which gives access to reliable temperature dependent recombination center properties. In this work we try to explain the influence of these recombination center properties and their temperature dependencies on measured device characteristics like reverse recovery, forward voltage and reverse current of freewheeling diodes (FWDs) with a blocking voltage of 1000V and 1200V.

TABLE I
SAMPLE TYPE OVERVIEW (CHIPS)

	Lifetime control	Manufacturer	
E	Electron irradiation	Semikron	development sample
EH	Electron/Helium irradiation.	Semikron	SKCD 11 C 120 I
PT	Platinum diffusion	Semikron	development sample
AU	Gold diffusion	IXYS	DSEI 12

II. SAMPLE OVERVIEW

Different diode samples are used for the experiments. Table I gives an overview about the different sample types and applied lifetime control techniques. Types E, EH and PT are samples with a blocking voltage of 1200V, type AU has a blocking voltage of 1000V. Types E and EH differ only by the Helium implantation.

III. PROPERTIES OF RECOMBINATION CENTERS

A Lifetime and center position

Carrier lifetime obtained from deep level recombination can be described by the Shockley-Read-Hall (SRH) statistics [23]. Assuming that excess carrier concentrations are equal, the SRH lifetime for a number of k independent deep levels is given by (1):

$$\frac{1}{\tau_{SRH}} = \sum_{i=1}^{k} \frac{n_0 + p_0 + \delta n}{\tau_{p0i}\left(n_0 + n_{1i} + \delta n\right) + \tau_{n0i}\left(p_0 + p_{1i} + \delta n\right)} \qquad (1)$$

In case of low-level injection $\delta n \ll n_0$ and in n-type silicon $n_0 \gg p_0$, (1) simplifies to (2) which shows that for recombination centers close to the middle of the band gap the low-level lifetime τ_{LL} is equal to the hole minority carrier lifetime τ_{p0}. Thus, low-level lifetime is controlled by traps with a level close to the intrinsic one.

$$\frac{1}{\tau_{LL}} = \sum_{i=1}^{k} \frac{n_0}{\tau_{p0i}\left(n_0 + n_{1i}\right) + \tau_{n0i}\ p_{1i}} \qquad (2)$$

At high-level injection, the excess carrier density is much higher than the equilibrium densities: $\delta n \gg n_0, n_1, p_0, p_1$. The high-level lifetime τ_{HL} is given by (3). The high-level lifetime does not directly depend on the recombination center position, but on trap concentration and capture coefficients. In many cases one center dominates high-level lifetime. Further, if one of the both capture rates c_n or c_p is apparently smaller than the other, the smaller rate controls high-level lifetime.

$$\frac{1}{\tau_{HL}} = \sum_{i=1}^{k} \frac{1}{\tau_{n0i} + \tau_{p0i}} = \sum_{i=1}^{k} \frac{1}{\frac{1}{c_{ni} N_{Ti}} + \frac{1}{c_{pi} N_{Ti}}} \tag{3}$$

Nevertheless, recombination center position has a strong influence on the carrier lifetime. In n-type semiconductors, the value of n_1 describes the position of recombination level. Since high-level injection is found only if excess carrier density δn is much higher than n_1, validity of this approach strongly depends on the value of n_1 which is given by (4). If this condition is not met, any measured high-level injection lifetime will apparently depend on excess carrier density. Further, the value of n_1 not only depends on recombination center position but of course also on temperature. This means, that influence of n_1 rises in case of shallow traps.

$$n_1 = n_i \, exp\left(\frac{E_T - E_I}{k_B T}\right) \tag{4}$$

The position of a recombination center influences also the generation lifetime in space charge regions, where we find a very low concentration of free carriers $n,p \ll n_i, n_1, p_1$. Thus, generation lifetime is found by (5):

$$\tau_{SC} = \tau_{p0} \, exp\left(\frac{E_T - E_I}{k_B T}\right) + \tau_{n0} \, exp\left(\frac{E_I - E_T}{k_B T}\right) \tag{5}$$

This means, that generation lifetime is controlled by the recombination center with a position closest to the middle of the band gap. Further, reverse blocking current is governed by the generation current (6) and rises with center positions closure to the intrinsic level.

$$J_G = \frac{q \, n_i \, A \, w_{SCR}}{\tau_{SC}} \tag{6}$$

B. Gold diffusion

Gold diffusion into silicon introduces an acceptor and a donor level in the energy gap which are not independent of each other. Since gold is used for long terms, center properties and their temperature dependencies are well known (Table II) [14]. Gold offers the best relation between forward voltage drop and switching properties.

TABLE II:
RECOMBINATION CENTER PROPERTIES OF GOLD [14]

Trap	Energy level	Capture coefficients c_n [cm³/s]	Capture coefficients c_p [cm³/s]
Acceptor	E_C-E_T=0.54eV	$1.64 \cdot 10^{-9} \left(\frac{T}{300K}\right)^{0.5}$	$1.737 \cdot 10^{-8} \left(\frac{T}{300K}\right)^{-1.5}$
Donor	E_T-E_V=0.35eV	$1.737 \cdot 10^{-7} \left(\frac{T}{300K}\right)^{-0.8}$	$6.755 \cdot 10^{-8} \left(\frac{T}{300K}\right)^{0.5}$

TABLE III:
RECOMBINATION CENTER PROPERTIES OF PLATINUM [11]

Trap	Energy level	Capture coefficients c_n [cm³/s]	Capture coefficients c_p [cm³/s]
Acceptor	E_C-E_T=0.228eV	$9.5184 \cdot 10^{-14} \cdot T^{2.5}$	$409.5 \cdot T^{-3.9}$
Donor	E_T-E_V=0.32eV	$15.62 \cdot T^{-3.5}$	$2.9 \cdot 10^{-9} \cdot T^{0.411}$

TABLE IV:
RECOMBINATION CENTER PROPERTIES IN IRRADIATED SAMPLES [22]

Trap	Energy level	Capture coefficients c_n [cm³/s]	Capture coefficients c_p [cm³/s]
E(90K)	E_C-E_T=0.167eV	$8.72 \cdot 10^{-8} exp\left(-\frac{T}{474K}\right)$	$6.39 \cdot 10^{-7} \sqrt{\frac{T}{300}} exp\left(\frac{6.15 \cdot 10^{-3}}{k_B T}\right)$
E(230K)	E_C-E_T=0.447eV	$3.41 \cdot 10^{-8} \sqrt{\frac{T}{300}} exp\left(\frac{22.13 \cdot 10^{-3}}{k_B T}\right)$	$2.79 \cdot 10^{-8} \sqrt{\frac{T}{300}} exp\left(-\frac{22.13 \cdot 10^{-3}}{k_B T}\right)$
H(195K)	E_T-E_V=0.351eV	$9.85 \cdot 10^{-9} \sqrt{\frac{T}{300}} exp\left(-\frac{85 \cdot 10^{-3}}{k_B T}\right)$	$4.3 \cdot 10^{-9} \sqrt{\frac{T}{300}}$

Unfortunately, the acceptor level nearby the intrinsic energy level acts as a very effective generation center which causes high leakage currents, especially at high temperatures. Further, Gold doped freewheeling diodes generate high voltage peaks during turn-on [16]. The gold profile after diffusion is U-shaped since gold shows a higher solubility in silicon in areas with high doping concentrations [17,19].

C. Platinum diffusion

Platinum generates two coupled defect levels, acceptor and donor, which control recombination processes (table III) [9,10]. Platinum is an effective recombination center at high injection (high current densities), whereas it acts only as a weak recombination center at low injection. Platinum shows a worse relation between forward voltage drop and switching properties, but it is possible to operate Platinum-diffused devices at higher temperatures due to the low leakage current. Another advantage is the low voltage peak during turn-on [13,16]. The physical properties are less well-known and published data lack of missing temperature dependencies [10,11,12]. The properties shown in table III are derived from data in [11]. The platinum profile is as in the case of gold U-shaped.

D. Irradiation induced defects

Irradiation of high energetic particles such as electrons, Hydrogen ions or Helium ions has been shown to be an effective lifetime killing technique with a good reproducibility. Irradiation generates different independent recombination centers in a semiconductors energy gap. Center composition depends on irradiation energy and annealing process. While electrons generate a homogenous recombination center profile; Hydrogen and Helium offer the possibility of local profiles. Table IV gives an overview of the determined trap parameters as used in our device simulations. The fundamental properties are found by DLTS measurements [20] applied to the irradiated samples investigated in this work. The hole capture coefficient c_p of the trap E(230K) is determined by leakage current measurements. The hole capture coefficient c_p of E(90K) is determined by DLTS measurements in electron irradiated p-type silicon. As DLTS measurements show, the electron capture coefficient of E(90K) is much smaller than the hole capture coefficient. Thus, according to (3), the electron capture coefficient of E(90K) controls the high-injection lifetime. This electron capture coefficient is determined by means of OCVD lifetime measurements [21] with optical generation of free carriers by means of laser light pulses in the temperature range of 250K to 425K [22]. E(230K) is found only in the Helium irradiated samples in low concentrations. In the electron irradiated samples E(230K) has been vanished due to the applied annealing temperature of higher than 300°C.

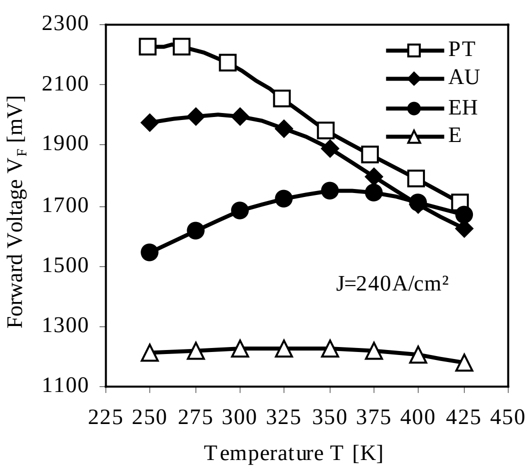

Fig.1: Temperature dependence of forward voltage at constant current

IV. FORWARD VOLTAGE DEPENDENCE ON TEMPERATURE

In figure 1, temperature dependencies of the samples are compared. In sample PT, the temperature coefficient is negative in the full temperature range, sample AU shows almost the same behavior with a slightly shift to lower forward voltage drops. At the electron irradiated sample E the temperature coefficient is practically linear while sample EH shows a positive temperature coefficient in a wide range. Since carrier mobility decreases with increasing temperature in a similar way in all samples, the differences of the forward voltages are strongly influenced by the temperature dependencies of the recombination centers capture coefficients. Nevertheless, the device structures or material properties are different - for example, thickness of the low-doped base region as well as the lifetime of the base silicon itself also affects forward voltage which makes it more difficult to identify the influence of recombination. For power devices, which are often paralleled in modules, it is important to achieve a positive temperature coefficient - higher at 400K than at 300K. Herein one of the main advantages of the irradiation technology as applied to sample EH is found.

V. REVERSE BLOCKING CAPABILITY

Reverse current is strongly influenced by position of deep traps. Table V shows the reverse current density at the maximum reverse voltage as stated in section II. As expected, the gold doped device shows the highest reverse current - at 400K it was only possible to measure the current for a blocking voltage of 800V due to the high reverse

TABLE V:
REVERSE CURRENT AT BLOCKING VOLTAGE (except:*V_R=800V)

Sample	Active area [cm^2]	Reverse Current I_R [mA]		Reverse Current Density J_R [mA/cm^2]	
		T=300K	T=400K	T=300K	T=400K
PT	0.31		0.62		2
AU	0.06	0.0075	18*	0.125	300*
E	0.06	0.00035	0.127	0.0058	2.1
EH	0.06	0.00044	0.44	0.0073	7.3

current and limitations of the measurement setup. The platinum doped sample shows the lowest reverse current due to the center properties. The concentration of the irradiation induced trap E(230K), which normally causes a higher reverse current density as found in sample E, is largely reduced by the high annealing temperature as mentioned before. But, this trap causes the higher reverse current of sample EH where it is found as a result of the Helium irradiation.

The high reverse current of gold at high temperatures, caused by the acceptor state in the middle of the band gap, is the reason for the limitation of using gold for lifetime control of power devices with blocking voltages not higher than 1kV.

VI. REVERSE RECOVERY PROPERTIES

During the reverse recovery process the stored charge inside the device is removed. Thus it is important to minimize the stored charge for lowering turn-off losses. Since wiring represents external inductances in the circuit, a large change in the di/dt gives rise to a large spike in reverse voltage which should be avoided. Figure 2 shows measured reverse recovery waveforms for the samples AU and EH while figure 3 shows the measurements for the sample E. Obviously, the electron irradiated sample E not only has the highest current peak but shows snappy behavior, generating voltage oscillations during turn-off, as well.

The comparison of samples AU and EH results in comparable current peaks of both samples while the EH-diodes stored charge is slightly larger than in the gold-doped device. It should be mentioned here that the only difference of the samples E and EH is the additional Helium irradiation which results in a local recombination center peak [1],[16].

The good recovery behavior of the gold-doped in comparison with the electron irradiated device is caused by the U-shaped recombination center profile while sample E shows a homogenous one [24].

A critical condition for the reverse recovery behavior of a freewheeling diode is low current. At rated current, which is typical about 150A/cm^2 for a 1200V device, it is possible to achieve soft recovery with gold or platinum diffused devices and a common optimization of the doping profile. But under normal operating conditions a sinusoidal current is often chopped at low current densities of about 10% of the rated current. There is another strength of the technology used for the EH device - soft recovery even at low currents.

Figure 4 shows as a result of device simulation the hole concentrations at different times of the samples E and EH at low current density. For these simulations we used the 2D device simulator TeSCA which includes an advanced recombination model considering a number of recombination centers [18]. The model makes use of the rate equations which take into account full trap dynamics and therefore dynamic effects in the space charge region of the power devices [15],[22]. The simulations explain the different

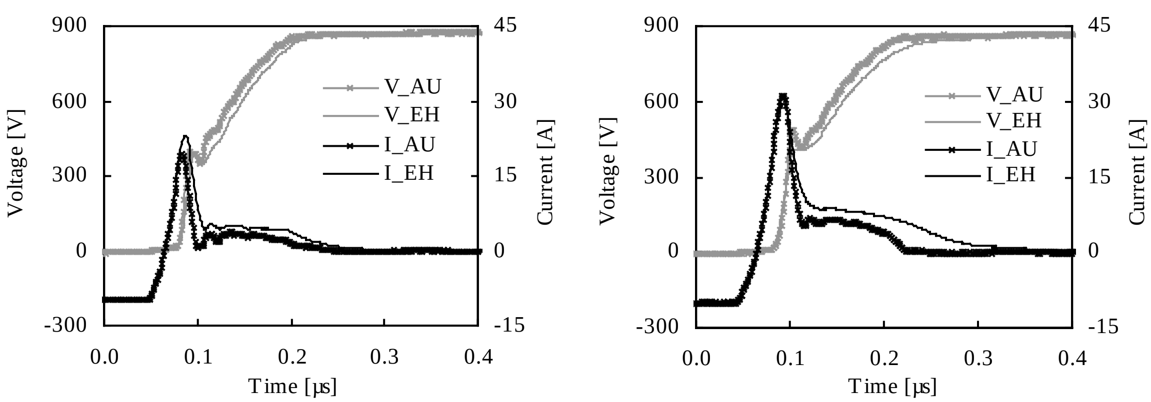

Fig.2: Reverse Recovery of samples AU and EH for T=300K (left) and T=400K (right) (I_F=10A,V_R=900V, di/dt=1.4kA/µs)

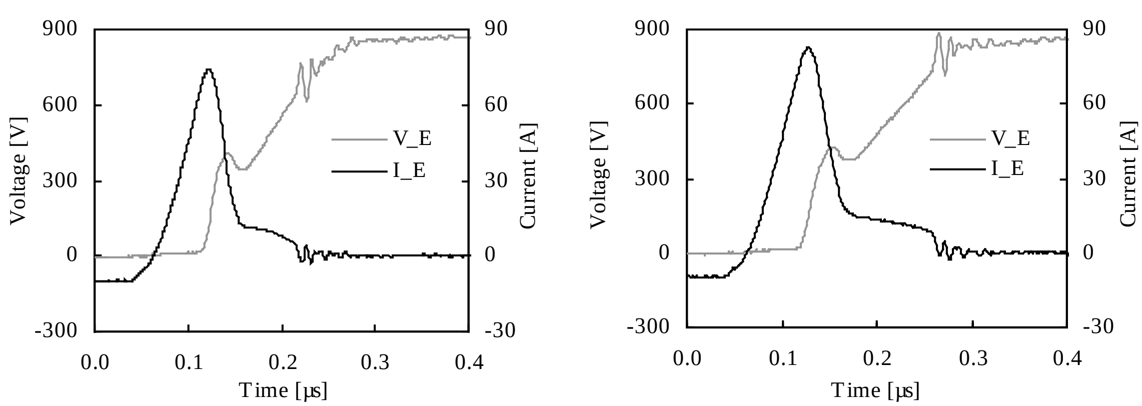

Fig.3: Reverse Recovery of sample E for T=300K (left) and T=400K (right) (I_F=10A,V_R=900V, di/dt=1.4kA/µs)

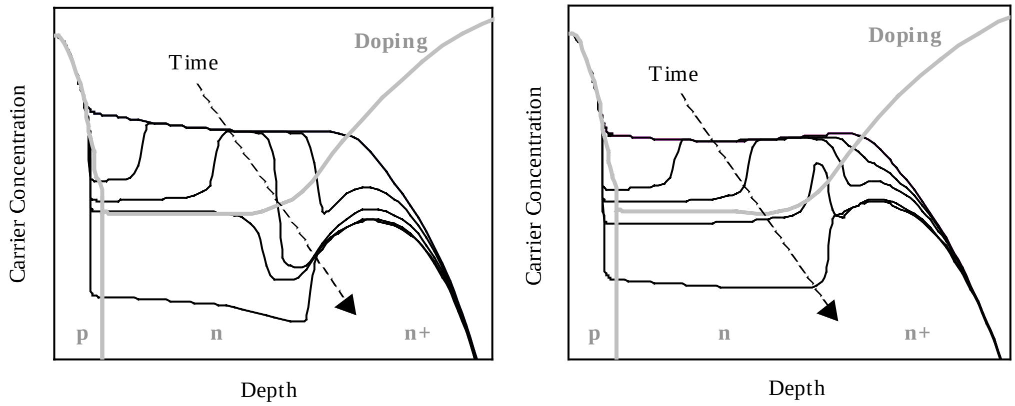

Fig.4: Carrier concentration during reverse recovery in a snappy (left) and a soft freewheeling diode (right)

reverse recovery behavior of the snappy sample E and the soft sample EH. In case of sample E (figure 4, left side) the number of carriers in front of the nn^+-junction reduces much faster than at the pn-junction. At the moment where the stored carriers at the nn^+-junction have vanished the reverse current jumps abruptly to zero and causes voltage overshoots and/or oscillations due to parasitic inductances. The reason for this behavior is found by the different carrier mobilities of electrons and holes. At the nn^+-junction the stored carriers are reduced by a electron current while the carriers at the pn-junction are removed by a hole current. Since the mobility of electrons is three times larger than the mobility of holes, the velocity of the electron carrier transport is three times larger than the velocity of the holes. To realize soft behavior, the number of carriers at the pn-junction should be lower than the number of carriers at the nn^+-junction as in case of sample EH (figure 4, right side). This could be attained by a number of methods as by reducing the Anode injection-efficiency or by a local lifetime reduction.

VII. CONCLUSION

Application of lifetime killing techniques offer not only significant improvements in the device behavior but also a possibility to take control on temperature dependence of a number of device properties. This has been shown on example of the behavior of devices, where different lifetime killing techniques were applied, in comparison with the dependence of recombination center properties on temperature. Furthermore, not only the properties of the recombination centers but also there profile effects the device behavior as was shown in case of reverse recovery characteristics.

VIII. ACKNOWLEDGEMENTS

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