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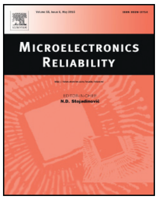

Influence of carrier lifetime distribution on the current filament in high voltage diode

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ABSTRACT

The current filament caused by strong dynamic avalanche during reverse recovery of a high voltage diode under extreme overstress conditions is an important factor of the device failure. The influence of carrier lifetime distribution on the current filament during reverse recovery of the high voltage diode was analyzed by the comparison between the uniform carrier lifetime distribution and the local low carrier lifetime distributions, and the variation process and the inhibition mechanism of the current filaments in diode were discussed. Electrothermal simulations show, how the local low carrier lifetime distributions can provoke the evolution of the anode-side current filaments and the appearance of multiple cathode-side current filaments. It is deduced that the low on-state plasma at the anode side is supposed to be the essential reason for the inhibition of the current filaments.

1. Introduction

The high voltage diode is turned off under overstress conditions, such as high d*i*/d*t*, high parasitic inductance *L* and high supply voltage V_{dc}, leading to the strong dynamic avalanche in the diode, so the non-uniform and high current density named current filament will appear [1,2]. Recent studies have shown that the appearances of the filaments at the anode and cathode sides do not necessarily lead to the diode destruction, however, the eventual filament by a transition from avalanche-induced into thermally driven filament could cause the local temperature rise inside the device, this is an important factor of the device failure [3–5]. In order to improve the fast and soft recovery characteristic of high voltage diode, some technologies by improved structures and carrier lifetime controls were implemented. In recent years, the carrier lifetime control technologies mainly include the high energy electron irradiation resulting in a uniform lifetime distribution [6–8], and the proton or He^{2+} irradiation providing a local low lifetime distribution [8–11]. The carrier lifetime distribution determines the on-state plasma distribution in the n^- base, which can influence the extraction velocity of the plasma and the power loss during reverse recovery, and what's more, it even influences the formation and movement of current filaments under dynamic avalanche [12–14]. This is very important for the device reliability.

Experimental verification is difficult to predict the failure mechanism of power device, so the electrothermal simulation is a very important method to analyze the influence of carrier lifetime control on the current filaments and present a deeper understanding of the failure mechanism of the high voltage diode.

In this paper, the influences of the uniform and local low carrier lifetime distributions on the current filaments were investigated, and the variation process and inhibition mechanism of the current filaments in high voltage diode were analyzed.

2. Diode structures and simulation models

In order to study the influence of carrier lifetime distribution on the current filament, three diodes with different carrier lifetime distribution models were established in Fig. 1. The uniform carrier lifetime in the diode D1 is $\tau_p = \tau_n = 1$ μs. The regions of low carrier lifetime located in the p^+ layers for the diodes D2 and D3 are both near the p^+n^- junctions, and $\tau_p = \tau_n = 0.05$ μs. The region of low carrier lifetime located in the n^- base for the diode D3 is near the n^-n^+ junction, and $\tau_p = \tau_n = 0.4$ μs. The vertical widths of low lifetime regions are 10 μm. For the 3.3 kV diode, the doping concentration of n^- region is 2.0×10^{13} cm^{-3}. The p^+ emitter and the n^+ emitter for three diodes have the same Gauss doping profile with the surface doping concentrations of 1.0×10^{19} cm^{-3} and 1.0×10^{20} cm^{-3}, and the depths are 25 μm and 10 μm, respectively. The lateral widths and thicknesses of the diode models are 2000 μm and 400 μm, respectively.

Fig. 2 shows the simulated test circuit of reverse recovery, in which $V_{dc} = 2.5$ kV, $J_F = 300$ A/cm^2, $L = 0.25$ μH and d*i*/d*t* = 10 kA/μs. The diode was analyzed under electrothermal simulation by the Sentaurus-TCAD simulator. A thermal resistance of 0.1 K/W was considered at the cathode side, and the initial temperature was set to 300 K. Auger and Shockley–Read–Hall recombination models, carrier–carrier

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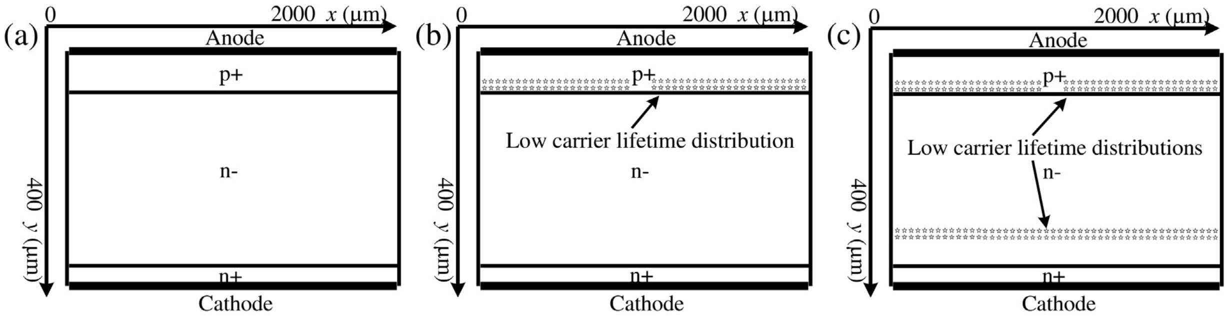

Fig. 1. (a) Schematic view of the diode D1 with a uniform carrier lifetime distribution, (b) Schematic view of the diode D2 with a low carrier lifetime distribution at the anode side. (c) Schematic view of the diode D3 with two low carrier lifetime distributions at the anode and cathode sides, respectively.

scattering, doping dependent and electric field dependent mobility models, and avalanche generation model were taken into account.

3. Influence of carrier lifetime on the current filament

During reverse recovery the holes in the n^- base are extracted towards the anode side, hence the hole density (p) adds to the background doping (N_D), and the effective doping, i.e. $N_{eff} = N_D + p$, leads to the increase of electric field strength. Therefore, the dynamic avalanche will occur, even the voltage is much lower than the static breakdown voltage [15,16]. In [4], the differences between the formation reasons and the variation behaviors of cathode side and anode side filaments were explained by analyzing the plasma front velocities during reverse recovery, and the results have shown that the filaments at the anode and cathode sides are both relevant to the negative differential resistance (NDR) in the *I*–*V* characteristic. After the plasma layer disappears, the current filament will connect the anode and cathode through the whole diode to maintain a positive feedback process in the impact ionization regions of both sides. Eventually, a single “winning” current filament carries the total current, resulting in a local melting of the diode [17].

3.1. Behavior of the current filament and discussion

The comparison of the on-state hole densities for three diodes under different current densities is shown in Fig. 3. The on-state voltage drop across the diodes D1 and D3 is approximate $V_F = 2.2$ V and for the diode D2 is approximate $V_F = 2.1$ V at $J = 100$ A/cm^2. For a standard diode with the highly doped emitters and a uniform carrier lifetime (D1), the on-state carrier profile is not uniform, and it is always higher at the pn$^-$ junction of the anode side than at the nn$^-$ junction of the cathode side, as shown in Fig. 3. However, the diodes with local low lifetime distributions (D2 and D3) show the inverted carrier profiles. This is in agreement with [18]. It is critical to obtain a soft recovery behavior.

The comparison of the reverse recovery characteristics for three diodes is shown in Fig. 4. Compared with the diode D1, the diodes D2 and D3 show the fast reverse recovery and lower peak current density, due to the lower on-state carriers and the less carriers generated by impact ionization during reverse recovery. The reduced carrier lifetime in the n^- base for the diode D3 causes a lower amount of carrier plasma at the cathode side compared with the diode D2 (Fig. 3). This leads to a faster recovery behavior. In Fig. 5 the diode D3 shows a slow temperature gradient, which leads to the reduction of maximum temperature.

The comparison of the current density distributions for three diodes at different times during reverse recovery is shown in Fig. 6. At 1.63 μs, for the diodes D2 and D3 the current filaments at the anode side have appeared, while the current filaments of the diode D1 occur later at 1.65 μs. This is because the plasma layer at the anode side for the diodes D2 and D3 is extracted faster than that of the diode D1, and the depletion layer at p^+n^- junction is built up earlier. However, over a short time, the dynamic avalanche has occurred at p^+n^- junction due to a high d*i*/d*t* (10 kA/μs), and a negative differential resistance appears at the anode side because of a space modulation effect of the electric field gradient by the free charge carriers [4], leading to the earlier appearance and non-uniform distribution of the current density.

Subsequently, at 1.66 μs, the current filaments at the anode side for the diode D1 begin rapidly evolving into the multiple current filaments. The current density inside the filament is high up to $J_{max} = 2246$ A/cm^2 (Fig. 7(a)), this leads to the appearance of a fixed and local melting current filament at the edge of the cathode side. However, for the diodes D2

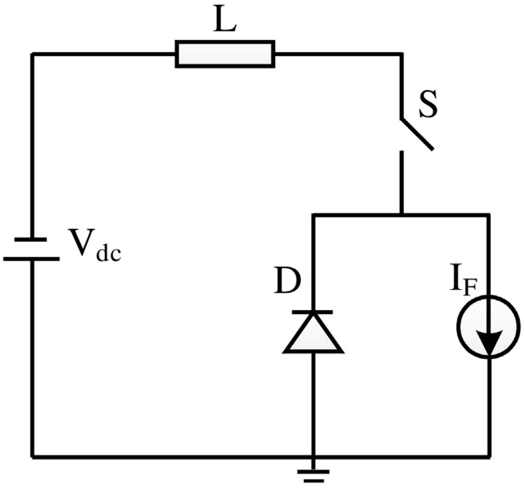

Fig. 2. Test circuit of reverse recovery for device simulation.

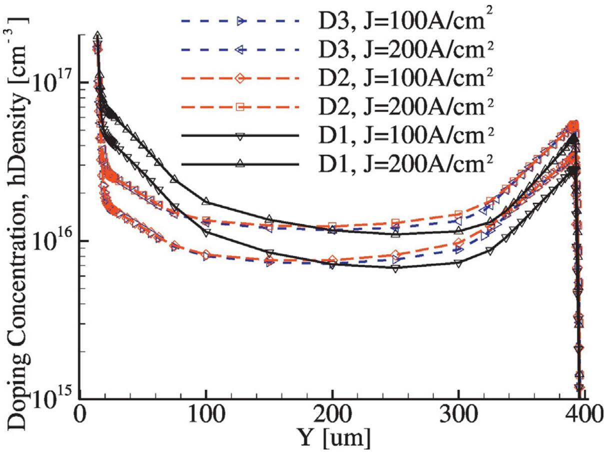

Fig. 3. The comparison of the on-state hole densities for three diodes under different current densities.