A NOVEL TYPE OF POWER PICOSECOND SEMICONDUCTOR SWITCHES BASED ON TUNNELING-ASSISTED IMPACT IONIZATION FRONTS

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Abstract

We propose a novel type of closing semiconductor switches based on a new physical mechanism – the propagation of a superfast tunneling-assisted impact ionization front. We present numerical simulations of the switching transients in the proposed devices. Our numerical results suggest that with the new mechanism, voltage pulses with a ramp up to 500 kV/ns and amplitude up to 8 kV can be formed. This sets new frontiers in pulse power electronics.

I. INTRODUCTION

Band-to-band impact ionization underlies the operation of many semiconductor devices, such as avalanche transistors, IMPATT- and TRAPATT-diodes, etc [1]. A very interesting mode of impact ionization breakdown is a superfast impact ionization front propagating from cathode to anode many times faster than the saturated drift velocity $v_s \sim 10^7$ cm/s. In semiconductor device physics, the wave-like mode of ionization breakdown has become known in connection with microwave TRAPATT-diodes [2]. Later on it was found that the breakdown of kilovolt p-n-junctions can also develop according to this scenario [3]. This discovery found important applications in pulse power electronics, underlying the operation of so-called Si sharpening diodes (SAS) [3-5]. These subnanosecond opening switches are used for sharpening electrical pulses, generating steep ($dU/dt \sim 10$ kV/ns) kilovolt voltage ramps. In a SAS diode the electrical field at the front edge is 200-500 kV/cm, which is above the threshold of band-to-band impact ionization of 200 kV/cm, but below of the threshold of band-to-band tunneling ionization (or Zener breakdown) of 10^3 kV/cm.

In this article we explore the dynamics of ionization fronts above the threshold of band-to-band tunneling breakdown. We demonstrate that the threshold of tunneling ionization can be reached under similar experimental conditions as for traditional impact ionization fronts in SAS-diodes. Typically a traditional superfast ionization front is triggered by applying a sharp voltage ramp (> 1 kV/ns) in the reverse direction to a p^+-n-n^+-structure switched in series with a load. This technique has allowed to reach a voltage ramp of up to 10 kV/ns as an output – the state of the art in the modern pulse power electronics. Our numerical simulations show that when such a sharp ramp of 10 kV/ns is applied as an input to a fully depleted reversely biased Si p^+-n-n^+-structure, the threshold of tunneling ionization 10^3 kV/cm can be reached before avalanche ionization starts. A new type of superfast front emerges that propagates due to the combined effect of tunneling and impact ionization. The new mechanism might allow to advance the parameters of SAS diodes by more than one order of magnitude, forming voltage ramps of up to 500 kV/ns for voltage pulses of 10 kV amplitude.

II. STRUCTURE AND MODEL

We study a Si p^+-n-n^+-diode with sharp junctions, 100 μm n-base and a cross-section of 0.002 cm^2. The n-base doping level is $N_d = 10^{14}$ cm $^{-3}$. These parameters correspond to a typical Si power diode with a stationary breakdown voltage of ~ 1.5 kV. The initially applied reverse bias is about $V_0 = 1$ kV, closely below the threshold of stationary impact ionization breakdown. The semiconductor switch is connected in series with a load that is taken 50-100 Ω in our simulations (Fig.1). The voltage pulse $V(t)$ applied to the structure and the load is approximated by linear function as

$$V(t) = V_0 + At. \qquad (1)$$

The voltage on the device is denoted as $U(t)$ and related to $V(t)$ through the Kirchhoff equation $V = U + RI$, where I denotes the current through the device. We keep $A = 10$ kV/ns hereinafter.

We use a minimal model which accounts for basic transport processes, for band-to-band impact ionization and for tunneling ionization. The transport is described in drift-diffusion approximation. The saturation of the drift velocity in high electrical field is taken into account. Continuity equations are solved together with Poisson equation and the Kirchhoff equation for the external

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circuit. Note, that since it is more convenient to work with positive electrical field for the reverse bias, we assume that the n^+-n-contact is on the left hand side and n-p^+-contact is on the right hand side in Fig.1 and Fig.3.

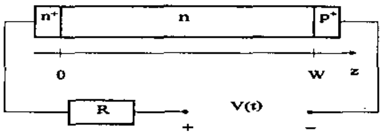

Figure 1. Sketch of the p^+-n-n^+-structure connected in series with load resistance R. The front is triggered near the n-p^+-contact and propagates to the left towards n^+-n-contact.

The tunneling from the valence band to the conduction band is described by [6]

$$G_T = \alpha_T E^2 \exp(-b_T / E), \tag{2}$$

$$\alpha_T = \frac{q^2}{3\pi^2\hbar^2}\sqrt{\frac{2m}{E_g}}, \qquad b_T = \frac{\pi}{4q\hbar}\sqrt{2mE_g^3}$$

where E is the absolute value of the electrical field, q and m are electron charge and effective mass, respectively, E_g is the bandgap, and $\hbar$ is Planck's constant. The impact ionization term is chosen as

$$\begin{aligned} G_I(n,p,E) = {} & \alpha_n(E)\, v_n(E)\,\Theta(n-n_{cut}) + \\ & + \alpha_p(E)\, v_p(E)\,\Theta(p-p_{cut}), \end{aligned} \tag{3}$$

$$\alpha_n = \alpha_{ns}\exp(-b_n / E), \qquad \alpha_p = \alpha_{ps}\exp(-b_p / E),$$

where n and p are electron and hole concentrations, respectively, and v_n and v_p are the corresponding drift velocities. The impact ionization coefficients and the characteristic fields are given by: $\alpha_n = 7.4 \times 10^5$ cm^{-1}, $\alpha_p = 7.25 \times 10^5$ cm^{-1}, $b_n = 1.1 \times 10^6$ V/cm, $b_p = 2.2 \times 10^6$ V/cm. The cut-offs n_{cut} and p_{cut} have been introduced to mimic the discreteness of the charge carriers. The simulations without the cut-off lead to qualitatively wrong results due to multiplications of unphysically small electron and hole concentrations which correspond to a tiny fraction of an electron or a hole in the whole volume of the device [7,8]. We refer to [8] for further details of the model and the numerical method.

III. NUMERICAL RESULTS

The external characteristics of the transient $V(t)$ and $I(t)$ are shown in Fig.2. Within the first ~ 720 ps the voltage on the device $U(t)$ increase linearly, following the applied voltage $V(t)$. During this delay stage the current in the device is the displacement current. The electrical field in the structure increases and soon overcomes the effective threshold of impact ionization 200 kV/cm. Despite of that, impact ionization does not develop because no initial carriers are available. After approximately 720 ps, when the voltage at the device is about 8 kV, the electrical field at the right boundary of the

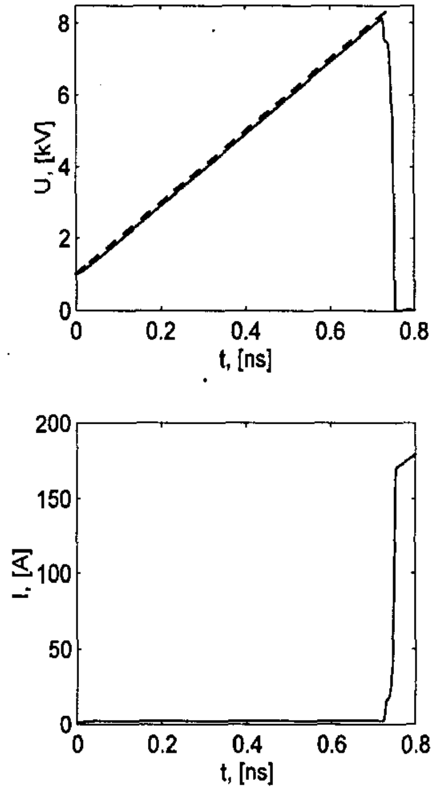

Figure 2. Voltage at the structure $U(t)$ and the total current $I(t)$ during the switching process. The dashed line on the upper panel denotes the externally applied voltage $V(t)$. Parameters: n-base width 100 μm, donor concentration in the n-base $N_d = 10^{14}$ cm^{-3}, device cross section $S = 0.002$ cm^{-2}, initially applied voltage $V_0 = 1$ kV, applied voltage ramp $A = 10$ kV/ns.

device, near the p^+-n-junction, reaches the threshold of impact ionization. By this time the electrical field is above the threshold of impact ionization everywhere in the n-base, and hence the avalanche impact ionization starts as soon as initial carriers appear due band-to-band tunneling. This is how this new type of ionization front is triggered.

The internal dynamics of carriers and electrical field during the front propagation is shown in Fig.3. The front propagates due to the combined effect of tunneling and impact ionization followed by Maxwell relaxation in the generated plasma and consecutive electrical screening. Tunneling generates initial carriers in the high field region at the edge of the ionization front. These carriers are multiplied further by impact ionization. In this way the high conductivity region that is filled with dense electron-hole plasma with concentration of $\sim 5 \times 10^{17}$ cm^{-3} expands, while the region of high electrical field shrinks. Though the impact ionization dominates the overall increase of concentration, the front propagation would not be possible without initial carriers provided by tunneling. For this reason we coin such front as *tunneling-assisted impact ionization front.* The front propagates with a velocity of approximately 4×10^8 cm/s, which is 40 times faster than the saturated drift velocity of the individual carriers v_s. This reflect the fact that front propagation is a collective process that is not based on drift motion of individual carriers.

As the front propagates, the current I increases and the voltage on the device $U(t)$ decreases due to the external circuit. Consequently, the voltage applied to the load increases. It takes ~ 30 ps for the front to cross the n-base. After the front has passed the n-base, the whole device is highly conducting. The voltage drops from 8 kV to the residual voltage of 10 V within these ~ 30 ps, applying a voltage pulse with an average ramp of 300 kV/ns to the load. The effective voltage slope is even steeper, approximately ~ 500 kV/ns. Hence the new mechanism has the potential to advance the operational parameters of SAS sharpeners by more than one order of magnitude.

IV. DISCUSSION

A. Requirements to the diode structure.

For the described mechanism it is essential that the n-base is free of mobile carriers during the delay stage, while the electrical field in the n-base increases. In view of this, the midgap energy levels represent an ultimate danger for the triggering, since these levels can assist in band-to-band tunneling or serve as electron traps capable to release a carrier in high electrical field. In both cases deep levels can act as an effective source of initial carriers leading to undesirable avalanche breakdown while the voltage is being increased [7]. In Si such levels can be associated with technological defects that appear as a side effect of widely used manufacturing technology during the heat treatment [9]. They are known as M, U and L-centers. It is noteworthy that most, if not all, SAS diodes presently in use have been manufactured according to this technology. Recently it has been suggested that the presence of these centers is absolutely crucial for SAS operation [7], since these centers provide initial carriers to trigger the front. In contrast, for the tunneling-assisted fronts considered here, it is necessary that the diode structure is free from all parasitic midgap levels.

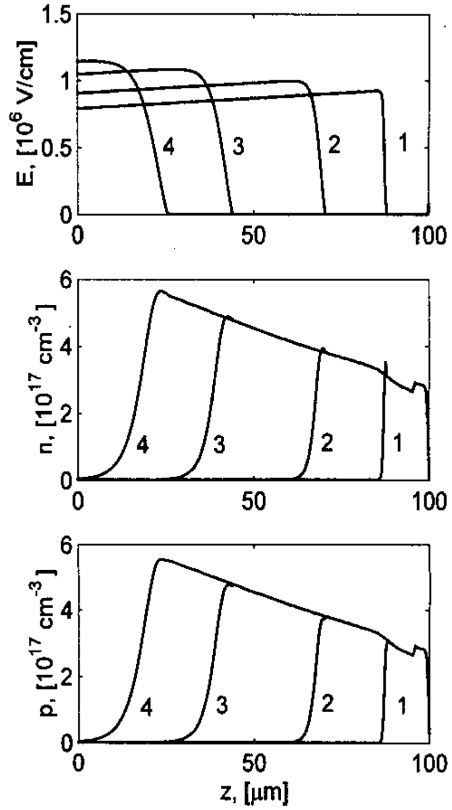

Figure 3. Snapshots of the electrical field profile and electron and hole concentration profiles in the n-base during the front propagation at times t = 735, 745, 750 and 752 ps (curves 1,2,3 and 4). Parameters as in Fig. 2.

Generally, a mobile carrier can also appear due to a random act of thermal ionization. However, it can be shown that even if this has happened, a solitary avalanche can not prevent the front triggering in the structure with large cross-section because the conductivity of the local channel created by the avalanche is insufficient to prevent voltage from increasing further. The probability that more than one carrier will be generated at room temperature within the delay time of 1 ns is negligible [8].

B. Transverse instability and current localization.

It is known that superfast impact ionization fronts may experience transverse instabilities and current localization, typically resulting in thermal destruction of the semiconductor structure [10,11]. It has been shown that both unstable and quasi-stable modes are possible for standard SAS diode [11]. Tunneling-assisted fronts might undergo a similar transverse instability, which can not be covered by the one-dimensional simulations presented here. Further analysis and multidimensional numerical modelling is required to clarify this question.

IV. SUMMARY.

Our numerical simulations suggest that the threshold of band-to-band tunneling ionization can be reached in Si sharpening diodes when a sufficiently sharp voltage pulse ($dU/dt \sim 10$ kV/ns) is applied to the structure in the reverse direction. The resulting breakdown takes the form of a superfast ionization front that propagates due to the combined effect of tunneling and impact ionization – the tunneling-assisted impact ionization front. A diode structure with a 100 μm n-base can switch within ~ 30 ps into the conducting state; during this time the voltage on the diode drops from 8 kV to the residual value of order of 10 volts. The voltage pulse applied to a 50 Ω load connected in series with the diode, has a ramp 300-500 kV/ns and an amplitude of several kilovolts, which is by more than one order of magnitude steeper than for SAS diodes presently in use.

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