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# Lucky-drift model for impact ionization in amorphous semiconductors

**K. Jandieri · O. Rubel · S. D. Baranovskii · A. Reznik · J. A. Rowlands · S. O. Kasap**

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**Abstract** A lucky-drift model for impact ionization has been recently successfully used to account for avalanche phenomenon in amorphous selenium (a-Se). We extend the calculations in order to compare the effect in a-Se with possible impact ionization phenomenon in another prototype amorphous semiconductor: hydrogenated amorphous silicon (a-Si:H). The results suggest that the higher phonon energy in a-Si:H as compared to a-Se shifts the threshold field for impact ionization in a-Si:H to essentially higher fields than those needed for avalanche multiplication in a-Se. Furthermore, it has been recently suggested that impact ionization is a precursor of the switching effect in the phase-change-memory materials ($Ge_2Sb_2Te_5$). We apply the lucky-drift model to $Ge_2Sb_2Te_5$ and show that it is capable to account for the magnitude of the electric field necessary to launch the electronic switching in this material.

## 1 Introduction

The process of avalanche multiplication of charge carriers in amorphous semiconductors, particularly in amorphous selenium (a-Se), known since many years [1–4] has received recently a significant attention of the scientific community due to the application of these materials in X-ray imaging devices [5–7] and in harpicon tubes—ultrahigh sensitive TV pickup tubes that use avalanche multiplication in a-Se to capture images at extremely low light intensities [8–10]. It has been well established experimentally [4, 5] that the avalanche phenomenon is observed in a-Se at electric fields above $8 \times 10^5$ V/cm.

One possible approach is to account for the effect is to apply to a-Se theoretical models initially proposed for crystalline semiconductors, for instance the Shockley lucky-ballistic model [11, 12] or the Ridley lucky-drift (LD) model [8, 13]. Another approach is to try to modify theoretical models developed for crystalline semiconductors taking into account specific features of amorphous materials. The latter attempt has been recently performed by Rubel et al. [14], who extended for amorphous semiconductors the LD model of Ridley taking into account elastic scattering on disorder potential inherent for amorphous materials. This scattering mechanism has not been included into the models for crystalline semiconductors. The approach has proven successful in the description of the avalanche multiplication in a-Se.

Although the LD model clarifies in a general way the origin of avalanche multiplication in amorphous media, it is still unclear why a-Se is still the only amorphous semiconductor that clearly evidences reproducible avalanche multiplication. Indeed, to the best of our knowledge, there is no direct and unequivocally clear experimental evidence on avalanche multiplication in any other amorphous material though there are arguments in favor of the existence of impact ionization in some chalcogenide glasses, viz., those based on Te, As, Ge and Si—Impact ionization was invoked to explain the threshold switching behavior in these materials. However, the results are somewhat contradictory and adequate

K. Jandieri (✉) · O. Rubel · S. D. Baranovskii
Department of Physics and Material Sciences Center, Philipps—University Marburg, 35032 Marburg, Germany
e-mail: Kakhaber.Jandieri@physik.uni-marburg.de

A. Reznik · J. A. Rowlands
Imaging Research, Sunnybrook Health Sciences Centre, Toronto, Canada M4N 3M5

S. O. Kasap
Electrical Engineering Department, University of Saskatchewan, Saskatoon, SK, Canada S7N 5A9

experimental support is still lacking. As for a-Si:H, most attempts to reach avalanche multiplication have been almost futile. For example, Futako et al. [15] prepared vidicon type *n-i-p* a-Si:H devices, and applied fields as high as 80 V/μm, and observed no avalanche multiplication in agreement with the experiments of Juska et al. [16] who applied fields as high as 50 V/μm. There is one interesting work reported by Akiyama et al. [17] in which the authors claim they have seen avalanche multiplication at fields above 150 V/μm. The latter authors use a double heterostructure type device, p-type a-SiC:H, i-type a-Si:H deposited onto an n-type crystalline substrate, to be able to apply extremely high fields. The reduced dark current in their a-SiC:H/a-Si:H heterostructure allowed higher fields to be reached due probably to a-SiC:H having a higher bandgap $E_g$ than a-Si:H. Since the ionization energy of impact ionization (i.e., the threshold energy for ionization) for many semiconductors typically decreases with the bandgap, it is quite surprising that while a-Se with $E_g = 2.0$–$2.3$ eV exhibits clear avalanche multiplication, the onset of impact ionization (if any) occurs at much higher fields in a-Si:H with $E_g = 1.7$–$1.8$ eV.

Recently Pirovano et al. [18] have suggested that impact ionization is responsible as a precursor for the switching effect in amorphous $Ge_2Sb_2Te_5$. The latter material is extensively studied as the basis for the phase-change memories. The authors observed a huge increase of electrical current at high voltages. They argue that the generation rate of charge carriers at high voltages is dependent not only on the magnitude of the electric field, but also on the carrier density. This observation indeed indicates the impact ionization as the underlying carrier generation mechanism.

In the current paper we apply the LD approach suggested in Ref. [14] to study the impact ionization in hydrogenated amorphous silicon (a-Si:H) and in a-$Ge_2Sb_2Te_5$. In Sect. 2 we briefly describe our version of the LD model. In Sects. 3 and 4 we apply this approach to a-Si:H and a-$Ge_2Sb_2Te_5$, respectively. Concluding remarks are gathered in Sect. 5.

## 2 Lucky-drift model for amorphous semiconductors

According to the LD model of Rubel et al. [14], charge carrier experiences elastic scattering on disorder potential and inelastic scattering on optical phonons while being accelerated by electric field. The particular formulation of this model sounds as follows. (i) The only elastic scattering process is scattering on disorderer potential; the mean free path for the elastic scattering is a model parameter $\lambda$; (ii) the loss of energy by a charge carrier in each collision with phonons is constant and equals to the optical phonon energy $E_{ph}$; the mean free path for the inelastic scattering is another model parameter $\lambda_E$; (iii) the collisions with phonons do not change the carrier trajectory essentially. An arbitrary path of a primary charge carrier during its drift as a series of $k$ elastic collisions and $m$ inelastic ones is considered. Further, the elastic collisions are divided in two subcategories: $k_l$ "lucky" collisions and $k_u$ "unlucky" ones. After a lucky elastic collision, the velocity of a primary carrier has a positive projection on the field direction and hence the carrier gains energy from the electric field after the scattering event. In the opposite case, a carrier loses its energy traveling against the field.

The resulting impact ionization coefficient (IIC) is calculated as:

$$\beta = \sum_{m=0}^{\infty} \sum_{k_u=0}^{\infty} \frac{P(k_u, m)}{l(k)}, \tag{1}$$

where the length $l(k)$ of the path for a charge carrier along the field direction after performing $k = k_l + k_u$ elastic collisions in order to attain the energy $E_I$ necessary for impact ionization, i.e., to create a secondary charge carrier was estimated [14] as

$$l(k) = \lambda(k_l \langle \cos \Theta \rangle + k_u \langle \cos \Theta^* \rangle). \tag{2}$$

$\langle \cos \Theta \rangle$ and $\langle \cos \Theta^* \rangle$ are the projections of the carrier velocity on the direction of electric field averaged over lucky and unlucky scattering events, respectively. The probability for charge carrier to experience the favorable for impact ionization chain of events

$$P(k_u, m) = P_{el}(k_u) P_{il}(k, m) \tag{3}$$

is a product of the probability $P_{el}$ to have $k_u$ unlucky collisions in the chain of $k$ elastic scattering events

$$P_{el}(k_u) = \frac{[k(1-W)]^{k_u}}{k_u!} \exp[-k(1-W)] \tag{4}$$

and the probability $P_{il}$ to have $m$ inelastic collisions in the same chain

$$P_{il}(k, m) = \frac{(k\lambda/\lambda_E)^m}{m!} \exp[-k\lambda/\lambda_E]. \tag{5}$$

In Eq. 4, $W$ is the probability for a carrier to be reflected within the angle $\Theta \leq \pi/2$.

The multiplication factor for the case that only one type of carriers experiences impact ionization depends on the thickness $d$ of the sample as

$$\eta^* = \exp(\beta d) \tag{6}$$

The quantity $\eta^*$ encompasses both the primary mechanism by which carriers are released after photon absorption and also the secondary mechanism by which free carriers can multiply, i.e., avalanche. It is the net effect that dictates the amount of mobile charge carriers generated by a single photon and therefore is the quantity of practical importance.

## 3 Comparison between a-Se and a-Si:H

In order to calculate the production of electron-hole pairs we need to specify material parameters $E_I$, $E_{ph}$, $\lambda$ and $\lambda_E$. Since for both a-Se and a-Si:H ionizing excitation across the mobility gap is much more probable than excitation from the localized states within the mobility gap, $E_I$ is assumed to be equal to the width of the mobility gap [19]. We start with applying our model to a-Se, where impact ionization and avalanche multiplication phenomena have been evidenced in numerous experimental studies. The "bandgap" of a-Se has been reported to be 2.0–2.3 eV in various previous studies depending on the type of measurement [20–23], and we take the least favorable for avalanche case $E_I = 2.3$ eV for the present work. The phonon energy $E_{ph}$ is taken equal to $E_{ph} = 31$ meV [24]. $\lambda$ and $\lambda_E$ are considered to be free parameters and are chosen from the best fit to the observed field dependence of IIC ($\lambda = 6$ Å and $\lambda_E = 72$ Å) [25]. The result for the field dependent multiplication coefficient for a-Se is given in Fig. 1.

Let us now consider conditions for impact ionization and possible avalanche multiplication in a-Si:H. The width of the mobility gap in a-Si:H is estimated as $E_I = 1.8$ eV [26]. In a-Si:H the phonon density of states is dominated by a strong peak at about 80 meV [27, 28]. Therefore, we assume $E_{ph} = 80$ meV for a-Si:H. Taking these estimates for $E_I$ and $E_{ph}$, and leaving the values of parameters $\lambda$ and $\lambda_E$ equal to those chosen above for a-Se, we obtain the field dependence of the multiplication coefficient for a sample with thickness 10 μm shown in Fig. 1, where it is compared with the corresponding result for a-Se sample of the same thickness. Theoretical results predict a considerable

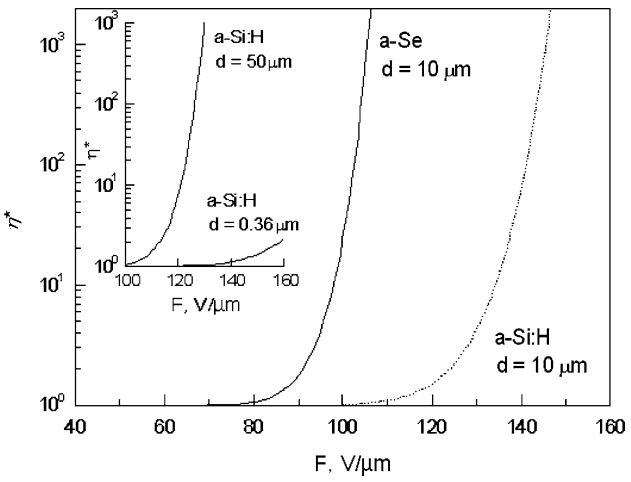


**Fig. 1** Multiplication coefficient versus electric field for a-Se ($E_I = 2.3$ eV, $E_{ph} = 0.031$ eV, $\lambda = 6$ Å and $\lambda_E = 72$ Å)—*solid line* and a-Si:H ($E_I = 1.8$ eV, $E_{ph} = 0.08$ eV, $\lambda = 6$ Å and $\lambda_E = 72$ Å)—*dotted line*. The sample thickness $d$ is assumed to be 10 μm. *Insert*: calculations for a-Si:H samples with thicknesses 50 and 0.36 μm

shift of the threshold field for impact ionization in a-Si:H with respect to that in a-Se. While in a-Se the avalanche begins at fields about 80 V/μm, the launch of the avalanche multiplication in a-Si:H is predicted for electric fields above 110 V/μm, provided parameters $\lambda$ and $\lambda_E$ have the same values in both materials. Remarkably the change of the sample thickness from 10 to 50 μm does not affect the threshold field significantly; see insert in Fig. 1. This shift of the threshold field for impact ionization in a-Si:H as compared to a-Se is apparently caused by essentially higher phonon energies in a-Si:H (80 meV as compared to 31 meV in a-Se). Due to higher phonon energies, the inelastic scattering processes in a-Si:H limit the energy gain of primary charge carriers in an electric field much more efficiently than in a-Se. Therefore one needs higher fields in order to achieve the impact ionization in a-Si:H even though the necessary ionization energy in a-Si:H is lower than that in a-Se. The results of our calculations can be considered as an explanation for the lack of observation of the impact ionization in a-Si:H up to 100 V/μm.

## 4 To the possible impact ionization in the phase-change memories

Phase-change technology is nowadays widely utilized in optical memory-storage devices [29]. In this application, a laser pulse focused onto the area corresponding to the bit size heats up the phase-change material making it locally changing between the amorphous and the crystalline phase. The difference in diffraction index of the two phases makes possible the optical read out. Since phase-change is also accompanied by a dramatic resistivity variation, the same material has been proposed for applications in semiconductor memories [30]. In this case, the idea is to electrically induce the phase-change and to associate the stored information to the corresponding high and low resistance values.

In the optical memories, transition between amorphous and crystalline phases is achieved by local hitting due to the absorption of light. In the case of semiconductor memories, the heating is driven by the current flow through the phase-transition region of the device. By increasing the bias, the current density becomes high enough to melt the material, and after switching the bias off, the molten material rapidly quenches in the amorphous phase. Transition back from amorphous to the crystalline phase can be obtained by applying the bias, which is high enough to generate the current flow that heats the phase-transition region but does not melt it to achieve a spontaneous crystallization [18].

Recently Pirovano et al. [18] have analyzed the electrical switching in $Ge_2Sb_2Te_5$ (GST) chalcogenide used for

the phase-change memory devices. By studying the current–voltage characteristic of GST, it has been shown that the material in the amorphous phase clearly evidences an abrupt transition from the low-conducting to the high-conducting state while passing over some critical value of the bias. Analyzing the current–voltage characteristic, Pirovano et al. [18] suggest the impact ionization of holes as a possible cause for the observed switching between two conducting states. Below we analyze this phenomenon in the framework of the LD model described in Sect. 2

It is known from experiment [18], that the switching in GST occurs at electric field of about 10 V/μm. In spite of the small thickness of the chalcogenide layer (~60 nm), the threshold field for switching is by an order of magnitude smaller than that corresponding to the onset of avalanche in a-Se. This difference can be caused by the lower energy gap of GST, which is about of 0.7 eV [18], and also by lower optical phonon energy, which is about of 20 meV [31].

In order to verify the impact ionization as a possible mechanism for the observed switching, we calculate the threshold field corresponding to the onset of avalanche in GST films. In the calculations we assume the ionization energy equal to the GST energy gap in amorphous phase, $E_I = 0.7$ eV, and the phonon energy equal to $E_{ph} = 0.02$ eV. Since elastic and inelastic mean free paths are *a priori* unknown, we take them similar to those in a-Se, i.e., $\lambda = 10$ Å and $\lambda_E = 70$ Å for elastic and inelastic scattering, respectively.

The field dependences of the impact ionization rate and the corresponding dependence of the multiplication coefficient calculated according to Eq. 6 for the sample thickness of 60 nm are given in Fig. 2. The theoretical data in Fig. 2b suggest the onset of impact ionization at the field of about 30 V/μm. We would like to emphasize that the calculated threshold field turns out to be of the order of experimental one even without adjusting the values of $\lambda$ and $\lambda_E$. Agreement between theoretical and experimental critical fields provides an additional argument in favor of the impact ionization as a possible switching mechanism in $Ge_2Sb_2Te_5$ amorphous chalcogenides.

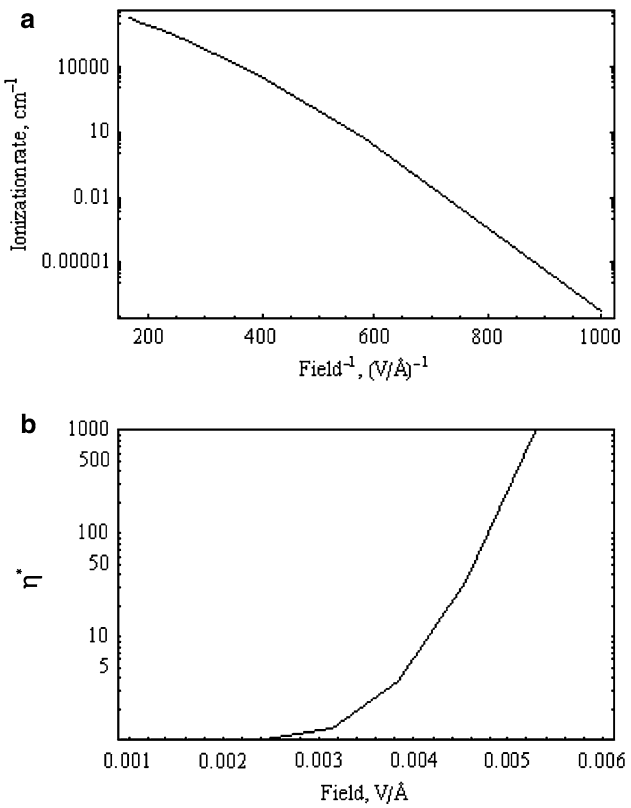


**Fig. 2** Impact ionization coefficient (**a**) calculated for $Ge_2Sb_2Te_5$ amorphous chalcogenide according to the modified LD model and the corresponding multiplication coefficient and (**b**) calculated according to Eq. 6 for the sample thickness of 60 nm. For the material parameters see text

## 5 Conclusions

Theoretical results are presented for the impact ionization in a-Se, a-Si:H, and a-$Ge_2Sb_2Te_5$ by means of the modified LD model taking into account elastic scattering on disorder potential inherent for amorphous materials and inelastic scattering on optical phonons. Comparison between a-Se and a-Si:H shows that in a-Si:H the impact ionization and avalanche multiplication phenomena can only be observed at much higher electric fields than in a-Se in agreement with experimental data. Higher phonon energies in a-Si:H as compared to a-Se are responsible for the less efficient gain of energy by the primary charge carriers in the electric field. Modified LD model also gives the critical field corresponding to the onset of the impact ionization in $Ge_2Sb_2Te_5$.

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