Optoelectronic bistability effect in semiconductors

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A recombination bistability driven only by light irradiance, without any intervention of an externally imposed electric or magnetic field, is possible in doped semiconductors in which recombination is assured by multiply charged centers. This effect is allowed by the competition between two or more different recombination channels, providing that the shallower charged centers capture more likely charge carriers of the same polarity than the deep neutral ones, in spite of columbic repulsion. A close algebraic condition guaranteeing this effect is given, involving the trap parameters of the recombination centers. Deep multiple recombination centers in germanium, silicon, and silicon carbide are identified whose trap parameters make those materials good candidates to the realization of optoelectronic switching devices based on this effect.

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I. INTRODUCTION

The study of the recombination instabilities in semiconductors is a field which is believed mature by most of the researchers involved. From late 1950s, negative conductivity regimes in lightly doped semiconductors was related to instable states of dynamic equilibrium in ionization-recombination processes, driven by impact ionization of impurities.[1,2] At the beginning of these studies, application was foreseen in switching devices and information storage (see, e.g., the cryosar[3,4]), but the expectations were frustrated by unavoidable emergence of deterministic chaos, resulting in unreliable switching.[5] If superheating mechanism[6] and effective-mass effects[7] can be excluded, the key role in the onset of instable regimes are played by avalanche-related phenomena, such as the screening effect of charge scatterers[8–11] or the excitation followed by ionization of metastable states of dopants.[12,13] The involvement of these effects in spatiotemporal complexity in recombination processes has been reported until now.[14,15] In fact, all the experimental and theoretical studies performed on recombination instabilities focalize on charge transport under electric fields which are high enough to initiate impact ionization of valence band or localized defects, which tends to evolve toward uncontrollable patternization (current filaments in biased semiconductors[15] or spots of high carrier density under microwave irradiation[14]).

Nevertheless, a recent theoretical investigation carried out by Lagomarsino[16] revealed that impact ionization, or also any other autocatalytic process, is only one of the physical effects which can drive to dynamical instability in recombination processes. The others are (i) tunneling between metastable states of impurity centers and (ii) multiple ionization of impurities. Both these phenomena can drive to the competition between two or more mutually dependent recombination channels, which are at the basis of a bistability effect potentially more reliable than those related to impact ionization. This is because they are related only to local light irradiance and not to the electric-field distribution. The second effect is the easiest to control by a suitable choice of the deep dopant and its concentration, but it requires, as a necessary condition, that charged centers capture carriers of the same sign (in spite of Coulombic repulsion) more efficiently than the neutral ones. This effect is possible in semiconductors because of the high energy transfer required by the recombination in deep centers, which make the multiphonon or radiative transition less likely than the phonon-cascade trapping by the shallower levels. In fact, several deep recombination centers in low-band gap semiconductors manifested this behavior since the very beginning of the studies on limiting charge lifetime centers.[17] Particularly, in the last years an extensive thermal spectroscopy study revealed that this behavior is quite common for transition metals in semiconductors.[18–22]

In this work, after a general introduction on the rate equations for deep, multiply charged centers (Sec. II), sufficient conditions on the recombination parameters are given, assuring multistability driven by over-band gap light irradiation in doped semiconductors, lightly compensated with doubly (Sec. III) and triply charged centers (Sec. IV). Eventually, a survey of the impurities in silicon, germanium, and silicon carbide which are good candidates to exhibit a multistable behavior is given along with a simulation of the expected temporal behavior for the most promising one that is nickel in germanium (Sec. V).

II. RATE EQUATIONS AND MULTIPLE STATES OF EQUILIBRIUM

We will study the response to an over-band gap irradiation of an extrinsic semiconductor lightly compensated with a deep recombination center which can trap up to Q electrons, then having $Q+1$ possible states of charge (see the scheme of Fig. 1). We want to ascertain under which conditions the system can access more than one state of dynamic equilibrium for some values of the generation factor g. We will assume the semiconductor to be of the n type. The case of p-type semiconductors can be obtained by simply exchanging the symbols p and n and reversing the levels order and the charge signs in the following considerations. We will denote with N and M, respectively, the concentrations of the shallow dopant and the deep recombination centers, with n and p the electron and hole density in the conduction and the valence band and with $L|e|$ the charge of the lowest level of

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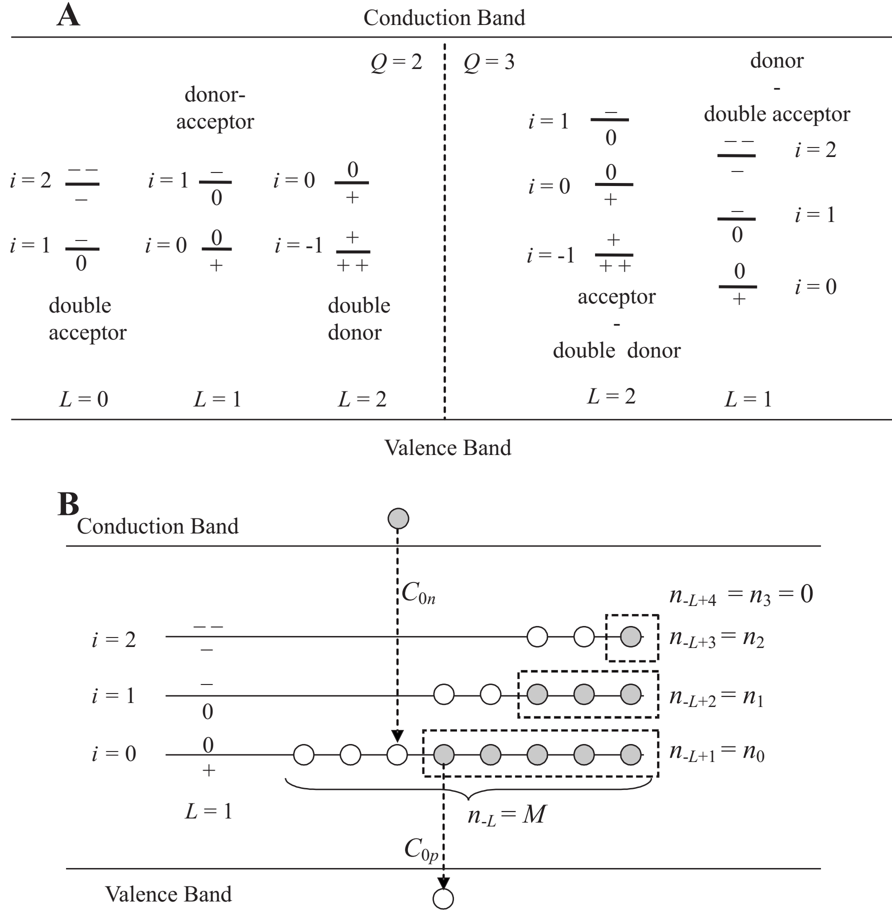

FIG. 1. Schematics of the (a) level structure and of the (b) occupation numbers of centers whose behavior is modeled by Eqs. (1)–(3).

the center. The index i labels the electronic levels, being $-i|e|$ the charge of the center when the level is occupied by an electron then $1-L \leq i \leq Q-L$. The density n_i is referred to the electrons in the ith state of the electronic configuration. See also Fig. 1 for a schematic of the level structure and for the conventions on the indexes.

The rate equations of the system are

$$\dot{n}_i = C_{in} n (n_{i-1} - n_i) - C_{ip} p (n_i - n_{i+1}), \tag{1}$$

with $n_{-L}=M$ and $n_{Q-L+1}=0$

$$\dot{n} = g - \sum_{i=1-L}^{Q-L} C_{in} n (n_{i-1} - n_i), \tag{2}$$

where C_{in} and C_{ip} are the capture coefficients for electrons and holes of the ith state. In the equations above the thermal transitions were neglected, assuming thermal energy to be much less than the activation energy of the levels. Equations (1) and (2) are bounded by the neutrality condition, which is

$$p = n - N - LM + \sum_{i=1-L}^{Q-L} n_i. \tag{3}$$

In the following, we will consider all the parameters and the unknown quantities expressed in terms of the following non-dimensional parameters:

$$x = \frac{p}{n}, \quad y = \frac{n}{N}, \quad y_i = \frac{n_i}{M}, \quad R_i = \frac{C_{ip}}{C_{in}},$$

$$K_i = \frac{C_{in}}{\left(\prod_{k=1-L}^{Q-L} C_{kn}\right)^{1/Q}}, \quad G = \frac{g}{NM\left(\prod_{k=1-L}^{Q-L} C_{kn}\right)^{1/Q}}. \tag{4}$$

As a consequence, Eq. (1) give, at equilibrium ($\dot{n}_i=0$), the following conditions:

$$y_i = \frac{\sum_{j=0}^{Q-L-i} x^j \rho_j^{Q-L}}{\sum_{j=0}^{Q} x^j \rho_j^{Q-L}}, \tag{5}$$

with

$$\rho_m^n = \prod_{k=n-m+1}^{n} R_k \quad \text{if } m \geq 1 \text{ and } \rho_m^n = 1 \text{ if } m < 1,$$

while relation (2) gives

$$y = G \frac{\sum_{j=0}^{Q} x^j \rho_j^{Q-L}}{\sum_{j=1}^{Q} x^j K_{Q-L-j+1} \rho_j^{Q-L}}, \tag{6}$$

and relation (3) gives

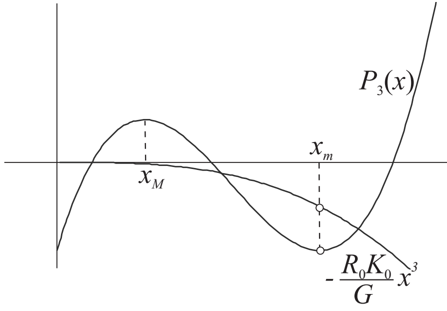

FIG. 2. Graphical representation of the solution of Eq. (11) and, in the limit $K_1 \ll R_0K_0$, of Eq. (20).

$$y = \frac{1}{1-x}\left[1 + \frac{M}{N}\left(L - \frac{\sum_{i=1-L}^{Q-L}\sum_{j=0}^{Q-L-i} x^j \rho_j^{Q-L}}{\sum_{j=0}^{Q} x^j \rho_j^{Q-L}}\right)\right]. \quad (7)$$

We are interested to know under which circumstances the system obtained by Eqs. (6) and (7) has more than one solution in the range $0 < x < 1$, corresponding to multiple states of dynamic equilibrium.

Unfortunately, the equation that solves this system is of degree $2Q+1$ in the unknown x, with little (if any) hope of algebraic discussion if $Q > 1$. Nevertheless, if the concentration of deep centers is much lower than that of the dopants ($M \ll N$), Eq. (7) reduces to

$$y = \frac{1}{1-x}, \quad (8)$$

and the solving equation is of degree $Q+1=3$ for doubly and $Q+1=4$ for triply charged centers. The form of the equation, in this case, is

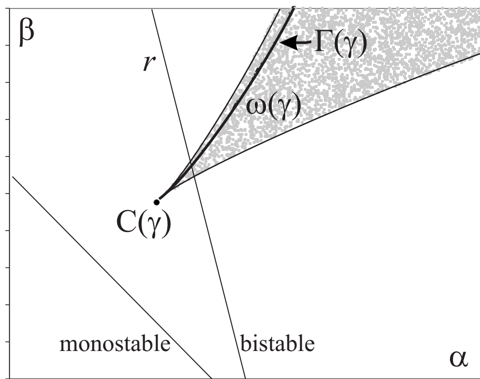

FIG. 3. The bistability region $\omega(\gamma)$ in the $\alpha\beta$ plane. If the straight line r crosses $\omega(\gamma)$, the behavior is bistable for some values of the generating factor g, otherwise the population of the bands is an one-value function of g. The curve $\Gamma(\gamma)$ beginning from the cusp point $C(\gamma)$ is included in region $\omega(\gamma)$.

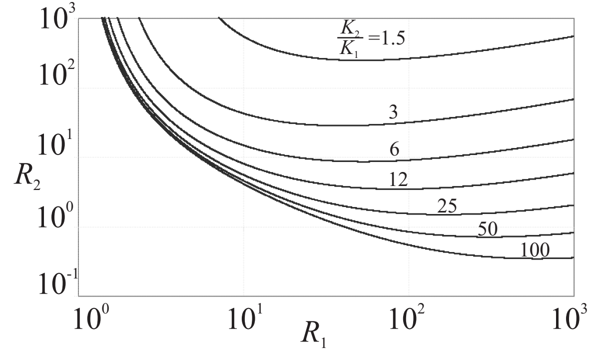

FIG. 4. Bistability occurs if and only if the (R_1,R_2) point is included in the convex region identified by a convenient value of $\frac{K_2}{K_1}$.

$$P_{Q+1}(x) = x^{Q+1} - \frac{1}{\rho_Q^{Q-L}} + \sum_{k=1}^{Q} \frac{1}{\rho_{Q-k}^{Q-k-L}}\left(\frac{K_{Q-k-L+1}}{G} + \frac{1}{R_{Q-k-L+1}} - 1\right)x^k = 0. \quad (9)$$

It is easy to verify that the solving polynomial $P_{Q+1}(x)$ assumes values of opposite sign in $x=0$ and $x=1$, that is, the equation has an odd number of solutions in the range $0 < x < 1$ no matter if Q is even or odd. As a consequence, in both cases $Q=2$ and $Q=3$, one or three states of equilibrium can hold, two stable and one instable in the latter case.

Reference 16 points out that a necessary condition for multistability in multiply charged systems is that the capture of a charge carrier is more probable when the center has captured another carrier of the same charge. In the present formalism, this means

$$K_{i+1} > K_i \quad \text{for some} \quad 1-L \le i < Q-L-1. \quad (10)$$

Relation (10) is only a necessary condition which is valid for every value of Q. In the following paragraphs, we will find sufficient conditions in a closed form, assuring multiple states of equilibrium in the cases of $Q=2$ and $Q=3$. These represent by far the most common cases of multiply charged recombination centers in semiconductors.

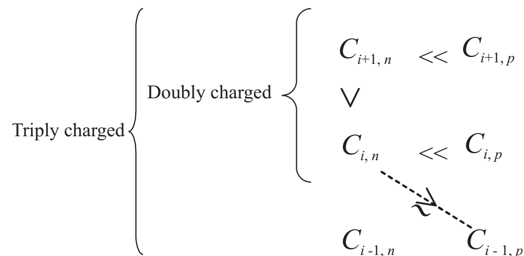

FIG. 5. Schematics of the relations between capture coefficients which give bistability in doubly and triply charged centers.

TABLE I. Capture cross sections of deep centers matching conditions (i) and (iii) of Sec. V. In the last column the values of $\frac{K_{i+1}}{K_i}$ and $\frac{K_{i-1}R_{i-1}}{K_i}$, which should be, respectively, greater than one and lesser or of the same order of one.

Recombination center, Q, L, doping, levels	E (eV)	C_n (cm^3 s^{-1})	C_p (cm^3 s^{-1})	$\frac{K_{i+1}}{K_i}$, $\frac{K_{i-1}R_{i-1}}{K_i}$
Cu in Si[a]				
$Q=3$, $L=2$				
p-type				$\frac{K_1}{K_0}(a)=\frac{C_{p0/+}(a)}{C_{p-/0}(a)}=83\gg 1$
$--/-$ $i=-1$	$E_c-0.167$	3.2×10^{-10}	6.5×10^{-6}	
$-/0$ $i=0$	$E_v+0.478$		2.9×10^{-7}	$\frac{K_1}{K_0}(b)=\frac{C_{p0/+}(b)}{C_{p-/0}(b)}=3.1>1$
$0/+$ (a) $i=1$	$E_v+0.207$		2.4×10^{-5}	
$0/+$ (b) $i=1$	$E_v+0.207$		8.9×10^{-7}	$\frac{R_{-1}K_{-1}}{K_0}=\frac{C_{n--/-}}{C_{p-/0}}=9\times 10^{-4}\ll 1$
Pd in Si[b]				
$Q=3$,$L=1$				
p-type				$\frac{K_2}{K_1}=\frac{C_{p++/+}}{C_{p+/0}}=8.3>1$
$-/0$ $i=0$	$E_c-0.23$	4×10^{-8}		
$0/+$ $i=1$	$E_v+0.31$		6×10^{-9}	$\frac{R_0K_0}{K_1}=\frac{C_{n-/0}}{C_{p0/+}}=6.7$
$+/++$ $i=2$	$E_v+0.14$		5×10^{-8}	
Ni in Ge (see Table II)				
$Q=2$,$L=0$				
n-type				
$--/-$ $i=2$	$E_c-0.08$	$\approx 1.5\times 10^{-8}$	$\approx 2\times 10^{-6}$	$\frac{K_2}{K_1}=\frac{C_{n--/-}}{C_{n-/0}}=6>1$
$-/0$ $i=1$	$E_c-0.39$	$\approx 2.5\times 10^{-9}$	$\approx 2\times 10^{-7}$	
Pt in 4H SiC[c]				
$Q=2$,$L=0$,				
n type				
$--/-$ $i=2$	$E_c-0.81$	5.3×10^{-8}		$\frac{K_2}{K_1}=\frac{C_{n--/-}}{C_{n-/0}}=1.3>1$
$-/0$ $i=1$	$E_c-1.46$	4×10^{-8}		

[a]Reference 18.
[b]Reference 20.
[c]Reference 22.

III. DOUBLY CHARGED CENTERS ($Q=2$)

The only doubly charged centers which satisfy the necessary inequality $K_{i+1}>K_i$, to my knowledge, are double donor impurities, for whom $L=0$. Then, for the sake of simplicity and without loss of generality, we can take $L=0$ and $Q=2$ in Eq. (9). In fact, one can obtain the general case by simply lowering the indexes of R_i and K_i of an amount L in case of $L>0$. We obtain

$$P_3(x)=x^3-\alpha x^2+\beta x-\gamma=0 \tag{11}$$

with

$$\alpha=1-\frac{1}{R_1}-\frac{K_1}{G},$$

$$\beta=\frac{1}{R_1}\left(\frac{K_2}{G}+\frac{1}{R_2}-1\right),$$

$$\gamma=\frac{1}{R_1R_2}. \tag{12}$$

The polynomial $P_3(x)$ has three roots in the interval $0<x<1$ (see also Fig. 2) if and only if the following inequalities hold:

$$\alpha>0,\quad \beta>0,\quad \gamma>0,$$

$$\left(\alpha^3-\frac{9}{2}\alpha\beta+\frac{27}{2}\gamma\right)^2<(\alpha^2-3\beta)^3. \tag{13}$$

In order to find conditions for bistability, one has to state which values of the parameters K_i and R_i make the coefficients α, β, and γ satisfying the inequalities (13) for some positive value of the control parameter G. Since G is not contained in γ, we can consider, for a given value of γ, the two-dimensional set $\omega(\gamma)$ of the couples (α,β) which satisfies the previous inequalities (13). The shape of $\omega(\gamma)$ is

TABLE II. Capture cross sections for nickel centers in germanium, as measured by several authors. All the authors but Klaassen which measured $\sigma_{n-/0}$ and $\sigma_{n--/-}$ give a ratio $\frac{\sigma_{n--/-}}{\sigma_{n-/0}}$ of about 6, compatible with bistability.

Author Method	$\sigma_{n-/0}$ Temperature	$\sigma_{n--/-}$ Temperature	$\sigma_{p-/0}$ Temperature	$\sigma_{p--/-}$ Temperature
Wertheim[a]	0.96×10^{-16} cm^2	5×10^{-16} cm^2		$100-400\times10^{-16}$ cm^2
PC	indep.	indep.		lowers with T
Tseng and Li[b]	1.4×10^{-16} cm^2	6.8×10^{-16} cm^2		40×10^{-16} cm^2
PC	300 K	300 K		300 K
Klassen *et al.*[c]	17×10^{-16} cm^2	2.3×10^{-16} cm^2	350×10^{-16} cm^2	$>1000\times10^{-16}$ cm^2
GR Noise		300 K	$\sigma_{200\ \mathrm{K}}\times T^{-1.5}$	300 K
Eliseev and Kalashnikov[d]	0.5×10^{-16} cm^2	3×10^{-16} cm^2		
PEM, PC, PC decay	300 K indep.	300 K indep.		
Kalashnikov and Tissen[e]		20×10^{-16} cm^2 150–300 K		200×10^{-16} cm^2 150–300 K
PC, PC decay				
Kotina *et al.*[f]		180×10^{-16} cm^2	8800×10^{-16} cm^2	
DLTS		105–125 K	95–110 K	
Rupprecht[g]			7000×10^{-16} cm^2	
Pulsed Field			$\sigma_{100\ \mathrm{K}}\times T^{-(0.5-1)}$	

[a]Reference 17.
[b]Reference 25.
[c]Reference 26.
[d]Reference 27.
[e]Reference 28.
[f]Reference 29.
[g]Reference 30.

shown in Fig. 3, with a cusp point $C(\gamma)$ whose coordinates are

$$C(\gamma)=(\alpha_\gamma,\beta_\gamma)=(3\gamma^{1/3},3\gamma^{2/3}). \tag{14}$$

By elimination of G in the first two equations of Eq. (12), we find that the coefficients α and β define a straight line r with a negative angular coefficient in the plane $\alpha\beta$. This line crosses the region $\omega(\gamma)$ if and only if the cusp point $C(\gamma)$ lies below it that means

$$\beta_\gamma+\frac{K_2}{K_1R_1}\alpha_\gamma<\frac{1}{R_1}\left[\frac{K_2}{K_1}\left(1-\frac{1}{R_1}\right)+\frac{1}{R_2}-1\right]. \tag{15}$$

From this expression, taking into account expressions (14) and (12), it turns out that recombination bistability is possible if and only if the following inequality holds:

$$3\left[\frac{K_1}{K_2}\left(\frac{R_1}{R_2^2}\right)^{\frac{1}{3}}+\left(\frac{1}{R_1R_2}\right)^{\frac{1}{3}}\right]+\frac{K_1}{K_2}\left(1-\frac{1}{R_2}\right)+\frac{1}{R_1}<1. \tag{16}$$

This inequality gives a necessary and sufficient condition to have photoconductive multistability driven by the generation factor g. In the three-dimensional space parameters given by R_1, R_2, and $\frac{K_2}{K_1}$, the region satisfying the inequality (16) is divided into two distinct branches. The first branch lies in the region with $\frac{K_2}{K_1}>1$ and $R_1>1$, and the second one in the "slice" $0<R_2<1$. Nevertheless, only the first branch has a physical meaning because the values of the parameters corresponding to the second branch give bistability only if $G<0$. The projection of the first branch on the R_1R_2 plane is shown in Fig. 4 for several values of $\frac{K_2}{K_1}$.

From the inspection of Fig. 4 we can set the rule of thumb according to which bistability occur if: (i) $\frac{K_2}{K_1}$ is large enough and in any case greater than 1. That is the charged center captures another carrier of the same charge more easily than the neutral one in spite of columbic repulsion; (ii) R_1 and R_2 are sufficiently large too and R_1 is in any case greater than 1. That is, the Coulombic capture cross section of the charged centers for the opposite-charged carriers is higher than that for the carriers of the same polarity (which is generally true).

The condition $\frac{K_2}{K_1}>1$ is obviously a particular case of relation (10), which is a necessary condition for dynamical instability referred to an arbitrary number of states of charge. Relation (16) also gives a sufficient condition for doubly charged centers.

It will be useful for the following considerations to infer the order of magnitude of the generation factor g and the time scale τ involved in the bistable transition. From Eqs.

(14) and (12), we have for the value G_γ at the cusp point $C(\gamma)$:

$$G_\gamma = K_1\left(1 - \frac{1}{R_1} - \frac{3}{(R_1R_2)^{1/3}}\right)^{-1}, \tag{17}$$

which gives, by relation (4), in the limit $R_{1,2} \gg 1$ [condition (ii)]:

$$G_\gamma \approx K_1 \quad \text{thus} \quad g_\gamma \approx NMC_{1n}. \tag{18}$$

The time scale τ can be obtained expressing Eq. (2) in terms of the adimensional parameters, which gives

$$\tau \frac{dy}{dt} = G - \sum_{i=1-L}^{Q-L} K_i y(y_{i-1} - y_i),$$

with

$$\tau = \frac{1}{M\left(\prod_{k=1}^{Q} C_{kn}\right)^{1/Q}}. \tag{19}$$

IV. TRIPLY CHARGED CENTERS (Q=3)

Triply charged centers in semiconductors have either a levels system with $L=1$ or with $L=2$. We will consider the first case, the second one being obtained formally by lowering of one unit the indexes in the coefficients R_i and K_i. Then the solving equation of the system [Eq. (9)] reduces to the form

$$P_3(x) = R_0\left(1 - x - \frac{K_0}{G}\right)x^3, \tag{20}$$

where parameters α, β, and γ in $P_3(x)$ are the same as in relation (12).

We will restrict our analysis to the centers for which the sufficient condition (10) ($K_{i+1} > K_i$) is satisfied. It can be found in literature that all of them have the indexes i and $i+1$ corresponding to the higher states of the configuration (levels 1 and 2 in our case). Thus, in order to find a sufficient condition for bistability, we will assume at first that the coefficients of the levels 1 and 2 satisfy relation (16), then assuring multistability if the level 0 could not be present. Second, we will find conditions on the capture coefficient of the lowest level which are sufficient to preserve the bistable behavior of the highest ones. On an intuitive basis, we can argue that the probability of capturing a hole of the neutral center should be smaller than that of capturing an electron because in the former case an alternative recombination channel will act in competition with the bistable one. The analysis below will show the validity of this insight.

Now, the order of magnitude of G, if the bistability is assured by levels 1 and 2, should be that of K_1, as seen in Eq. (17), then $\frac{K_0}{G} \approx \frac{K_0}{K_1} = \frac{C_{n0}}{C_{n1}}$. Since the 0 level is positively charged when empty (level 0/+) we can assume that $C_{n1} \ll C_{n0}$, that is $\frac{K_0}{G} \gg 1$. Consequently, the right-side polynomial of Eq. (16), in the interval $0 < x < 1$, reduces to $-\frac{R_0K_0}{G}x^3$, which is negative, and if we assume that the equation $P_3(x)=0$ has three solutions in the same interval, a sufficient condition for Eq. (20) to have the same number of solutions is the following:

$$P_3(x_m) < -\frac{R_0K_0}{G}x_m^3, \tag{21}$$

where x_m is the point where the polynomial $P_3(x)$ has a relative minimum (see also Fig. 2). Now, relation (21) has to be verified for some of the values of (α,β) which belong to the region $\omega(\gamma)$ for a fixed value of γ. It is easily shown by inspection of relation (13) that the curve $\Gamma(\gamma)$, whose equation is

$$\alpha^3 - \frac{9}{2}\alpha\beta + \frac{27}{2}\gamma = 0, \tag{22}$$

is totally included in the region $\omega(\gamma)$ if $\alpha^2 - 3\beta \geq 0$. Moreover, this equation, in the case $\gamma \ll 1$ (that is $R_{1,2} \gg 1$) reduces to the simpler form

$$\beta = \frac{2}{9}\alpha^2. \tag{23}$$

It can be proved, by substitution of Eq. (23) in relation (21) and imposing $\gamma \approx 0$, that all the coefficients α are simplified in the inequality (21). Thus, the same reduces to

$$\frac{R_0K_0}{G} < \frac{6\sqrt{3}}{(3+\sqrt{3})^3}, \tag{24}$$

which, assuming $G \approx K_1$ [see Eq. (18)], means

$$\frac{R_0K_0}{K_1} = \frac{C_{0p}}{C_{1n}} < 0.1. \tag{25}$$

The inequality (25), providing that R_1, R_2, K_1, and K_2 satisfy Eq. (16), gives a sufficient condition for bistability. As a matter of fact, this condition seems to be quite restrictive; numerical simulation shows that bistability occurs, depending on the values of all the other parameters, for values of $\frac{C_{0p}}{C_{1n}}$ up to some unit. Interestingly, in triply charged centers the capture coefficient for electrons of the lower level C_{0n} does not affect the dynamical stability of the system.

V. DEEP CENTERS CANDIDATE TO EXHIBIT BISTABILITY

On the basis of the considerations of the preceding Secs. III and IV, a bistability in the band populations of semiconductors, driven by light irradiance, is possible if recombination is assured by centers having multiple states of charge, namely, $-(i+1)|e|$, $-i|e|$ for doubly charged centers and also $-(i-1)|e|$ in case of triply charged centers. Conditions for bistability are (see also the resume offered in Fig. 5): (i) The capture probability of an electron is higher for a center which have previously captured another electron. That is $\frac{K_{i+1}}{K_i} = \frac{C_{i+1,n}}{C_{i,n}} > 1$; (ii) The capture probability for holes of the two higher levels is greater than that of the electrons. Formally,

$R_i = \frac{C_{i,p}}{C_{i,n}} \gg 1$ and $R_{i+1} = \frac{C_{i+1,p}}{C_{i+1,n}} \gg 1$ with R_i, R_{i+1}, and $\frac{K_{i+1}}{K_i}$ bounded by relation (16); (iii) In case of triply charged impurities, a center which can trap two electrons has a capture cross section for a hole of the same order of magnitude, or lesser, than that for the electrons. That is, $\frac{K_{i-1}R_{i-1}}{K_i} = \frac{C_{i-1,p}}{C_{i,n}}$ is lesser than some units.

The considerations written above are valid for n-doped semiconductors, but they can be trivially extended to p-type materials reversing the levels order and exchanging the terms "electron" and "hole" and the symbols n and p in the formulae.

The first property (i) has long been reported for nickel in germanium[17] and recently for platinum in 4H silicon carbide.[22] Moreover, extensive studies performed on deep levels in silicon permit to assess that it is quite common for transition metals impurities.[18–21] Among these, copper and palladium exhibit also property (iii) (see Table I) and are good candidates to serve as deep dopants in a photoconductive bistable device. Nevertheless, an ultimate statement about the feasibility of a device based on this effect requires the test of condition (ii), hence a thorough characterization of all the capture coefficients, both for electrons and holes. Such a thorough characterization has been carried out, in silicon, for zinc[23] (double donor) and titanium (double acceptor),[24] by means of transient capacitance measurements (double pulse method), but those impurities do not have the property (i) and therefore cannot exhibit a bistable behavior.

Among doubly charged centers, nickel in germanium is probably the more investigated one having $\frac{K_2}{K_1} > 1$, but the conclusions reached about its capture rates are not unanimous (see Table II). To my knowledge, there are three works offering a quite complete picture of the recombination coefficients, based on different experimental techniques, along with a number of studies giving one or two among the four capture rates. Klaassen *et al.*[26] obtains $\frac{K_2}{K_1} = 0.14 < 1$ by generation-recombination noise measurements, but Wertheim,[17] Tseng and Li,[25] and Eliseev and Kalashnikov[27] obtain $\frac{K_2}{K_1} = 6 > 1$ with photoconductive methods. Wertheim and Tseng and Li give three of the four coefficients necessary for the calculation of relation (10) (K_1, K_2, and R_2). Wertheim obtains $20 < R_2 < 80$ which could give bistability, according to relation (10) if $R_1 > 5$, that is $\sigma_{1p} > 5 \times 10^{-16}$ cm^2. This inequality is largely satisfied by the values of σ_{1p} obtained independently by all the other researchers (see Table II) at sufficiently low temperatures. Tseng and Li, on the other hand, give a value of $R_2 \approx 5$, which is slightly too small to permit bistability, also with very large values of R_1. In conclusion, there is conclusive evidence, by photoconductive measurements, that the necessary condition $K_2 > K_1$ is satisfied for nickel in germanium; moreover, there are suggestions that also the sufficient condition of relation (16) is satisfied for this center, at least at low temperatures (≈ 100 K).

A numerical simulation of the behavior of n-doped germanium, lightly compensated with nickel, has been carried out, solving Eqs. (1) and (2), with condition (10). The parameters were those given by Wertheim,[17] along with $\sigma_{1p} \equiv \sigma_{p-/0} = 10^{-13}$ cm^2, which is a conservative estimate based on the values of Table II. The doping centers and the recombination center concentrations were, respectively, $N = 10^{16}$ cm^{-3} and $M = 5 \times 10^{14}$ cm^{-3}. Figure 6 represents the hysteresis cycle of the valence-band population, as a function of the generation factor, and the inset represents the response of the valence-band population to pulses above and below the bistable interval. For the values of the parameters given above, bistability occurs for generation factors $g \approx 7.5 \times 10^{21}$ cm^{-3}s^{-1} which are obtained, for an over band-gap radiation with a penetration length of 100 μm, at a power density of about 8 W/cm^2. Transitions on-off and off-on occur with pulses of at least 2 μs of duration. The transition time and the power density, according to relations (19) and (18), scale as $\frac{1}{M}$ and $N \times M$, respectively, which could give a slight freedom of choice in the band gap engineering to achieve a bistable photoconducting behavior.

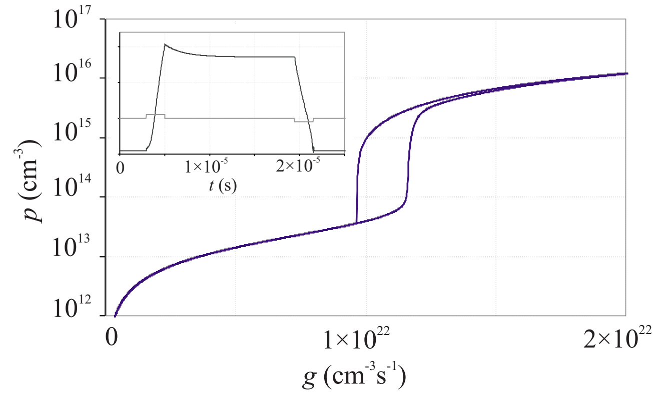

FIG. 6. (Color online) Simulated hysteresis circle of the valence-band population in Ni-doped germanium, obtained varying the generating factor sinusoidally, between 0 and 2×10^{22}(cm^{-3} s^{-1}), with a period of 150 μs. The values of the trapping parameters are those given by Wertheim (Ref. 17) specified in the text of this article. In the inset, simulation of the transition profile of the valence-band population in Ni-doped germanium, for a fixed value of the generating factor, with short pulses over and under the bistable range.

If a photoconduction experiment is performed in the current regime,[31] with a ballast resistance between the sample and a dc power supply, the bistability effect should be detected also with an electric field as low as 1 Vcm^{-1}, measuring the voltage drop across the photoconductor. This electric-field intensity is well below the limit for impact ionization of impurities in germanium[32] and could not be mistaken with any avalanche-related bistability effect.

VI. CONCLUSIONS

The possibility of a new optoelectronic bistability effect in photoconductors is stated based on a recombination instability in semiconductors lightly compensated with multiply charged centers. Several candidates for the realization of a switching device driven by an external radiation source are offered by the literature, namely, copper and palladium in silicon, platinum in silicon carbide, and nickel in germanium; the last being the more promising one. A photoconduc-

tion experiment at low electric field (in order to avoid avalanche phenomena) and at different temperatures would be useful to detect the bistable behavior in germanium. An experimental effort could also be appropriate to perform a thorough characterization of the capture coefficients of the centers in silicon and silicon carbide, in order to verify, by testing of property (ii) (Sec. V), if they can exhibit photoconductive bistability.

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