Solid-State Electronics Vol. 32, No. 8, pp. 593–601, 1989
Printed in Great Britain.

0038-1101/89 $3.00 + 0.00

HEAVY DOPING EFFECTS ON THE *I–V* AND STORED CHARGE CHARACTERISTICS OF NARROW BASE PIN DIODES

ALEXANDRU MÜLLER and SORIN VOINIGESCU†
Research & Development Center for Electronic Components, Str., Erou Iancu Nicolae 32 B, Sector 2, 72996, Bucharest, Romania

(*Received* 29 *January* 1988; *in revised form* 31 *January* 1989)

Abstract—A novel model for the $I = I(V)$ and $Qs = Qs(I)$ characteristics of narrow base pin diodes is developed. For the first time, heavy-doping effects are taken into consideration leading to a remarkable agreement (within 10%) with experiments carried out on *S*, *X* and *K*-band step-recovery diodes. Accordingly, the stored charge becomes an accurately predictable parameter. This paper also contributes to the better understanding of heavy-doping parameters in p^+ silicon such as deriving new values for minority electron mobility and analysing the recombination effects on the *I–V* characteristics of transparent and quasi-transparent p^+ emitters. Somewhat surprisingly, even for 1.5 μm emitters, the transparent emitter model appears to provide better correlation with experiments than the quasi-transparent emitter one. It is found that improvement of the latter model's agreement with experiment asks for lower Auger coefficient values (*Cp*) than currently available ones.

1. INTRODUCITON

The detailed prediction of the *I–V* characteristic and switching behaviour of narrow-base pin diodes is important for semiconductor device physics and applications in microwave switching- and step-recovery devices[1–3]. In the latter cases, the switching behaviour is essential for device operation and design but the requirements are entirely different: for switching pin diodes the storage time should be made as short as possible, while for step recovery devices the storage time has to be enhanced and the transition time reduced.

There is a significant difference between the switching behaviour of narrow- and that of long base pin diodes (Fig. 1). In the latter, the storage and transition periods are comparable in duration to the carrier lifetime in the base. In narrow base pin diodes, however, the transition phase is 2–3 orders of magnitude shorter than the storage phase. Due to the step recovery, the stored charge *Qs* and the storage time *Ts* are linearly related, *Qs* being independent on the magnitude of the reverse voltage pulse.

$$Qs = \int I_R \, d\tau \simeq I_R Ts.$$

As a consequence, in the following analysis, it is more convenient to concentrate on the stored charge *Qs*, rather than on the storage time *Ts*.

The paper is first involved with a new approach for the investigation of the *I–V* characteristics. To these authors' knowledge, it is the first time that heavy-doping effects (bandgap-narrowing, hopping conduction in band tails position dependent acceptor levels[4–6]) are included in the modelling of these devices. The third section presents a novel derivation of the stored-charge characteristics. The stored charge is found to be a predictable device parameter. It is proven that, as long as the emitter is transparent, the stored charge is independent of the lifetime in any region of the diode. This conclusion contradicts previous models[1,2] which claim that recombination in the base governs the carrier distribution and device operation. The latter feature is valid only in long-base pin diodes. Other previous treatments of the problem (based on the pioneering work of Moll *et al.*[3]) refer to an artificial "effective carrier lifetime" related to diode geometry and impurity profile.

The development of the present theory has, as a side effort, led to a revision of the minority electron mobility model in p^+ silicon. The latter is strongly supported by the extensive *I–V* and *Qs–I* measurements, described in the final section, on several types of narrow-base pin diodes.

2. UNDERLYING PHYSICS

2.1. Basic assumptions

In narrow base ($w \ll L_{\text{diffusion}}$) pin diodes the electric field created by the majority carrier gradients in the close vicinity of the junction, and not the lifetime, plays the essential role in the determination of the carrier distribution and the value of the stored charge. Due to the thin base, the carrier profile in the *i* region is practically constant. For the same reason, the stored charge in the p^+ and n^+ regions can no

†Present address: Electronics Department, Polytechnic Institute Bucharest, Romania.

longer be neglected. Throughout the rest of this paper the following assumptions are considered valid:

(a) The low-doped region operates under high injection level, while the high-doped regions function at low injection levels.
(b) Bulk recombination is neglected in the base and infinite recombination velocity is assumed at the contacts.
(c) The p^+ emitter is quasi-transparent[7]
(d) The analysis is 1-D in space.

These assumptions are minor restrictions for the real narow-base diodes. The first condition is fulfilled in the normal range of bias currents for these devices (i.e. 100 μA $\cdots$ 50 mA). The second one is insured by the thin base, as will be revealed by comparison with the results of other authors who have included bulk recombination in full computer simulations. Surface recombination, on the other hand, is less predictable but there appears to be a general consensus that it occurs with infinite velocity at ohmic contacts (this being the case of the devices in this study). Condition (c) is strictly valid for shallow emitters and its range of validity will be fully addressed later. The final assumption is typical for bulk- or interface perpendicular conduction devices, where 2-D effects are insignificant.

2.2. Heavy doping effects

The intensive studies carried out in the last decade for the investigation of carrier transport in non-uniform semiconductors[8–11] and the requirement for highly accurate models of the silicon bipolar transistor[7,12,13] have helped the better understanding of heavy doping effects. Even so, certain aspects of these phenomena are not entirely settled. More recent research[14,15] has experimentally revealed unusually low minority carrier mobilities (electrons and holes) in moderately and heavily doped silicon samples. Fossum *et al.*[6] have provided a phenomenological minority-mobility model, based on the concept of hopping conduction through valence band tails in n^+ emitters, a model sustained by bandgap narrowing measurements. Although, to these authors' knowledge, no measurements have previously been performed on p^+ emitters, the same model is employed here in the investigation of pin diodes.

The model accounts for the following heavy-doping-related effects:

(i) bandgap narrowing at moderate-to-high impurity doping[4]
(ii) impurity deionization via doping-dependent acceptor levels E_A, merging into the valence band in the p^+ region[5];
(iii) hopping conduction in band tails leading to several times lower minority carrier (as opposed to majority carrier) mobilities[6];
(iv) Fermi–Dirac statistics;

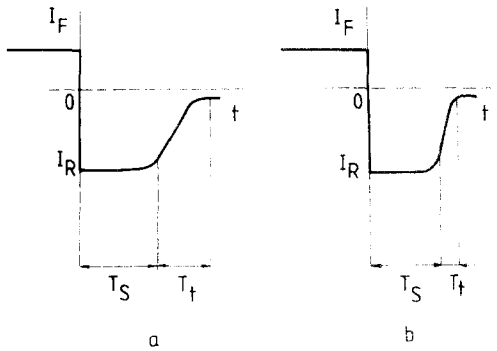

Fig. 1. Typical switching characteristic of long base (a) and narrow base (b) pin diodes.

(v) negligible influence of the degeneracy on the density of states in the conduction and valence bands, a restriction validated by experiments with doping levels up to 5×10^{19} cm^{-3} and, also, enforced by the lack of satisfactory models related to measured data[6,10].

2.3. The I–V characteristic

The experimental I–V characteristic of narrow base pin diodes exhibits a relatively wide current range (between several hundred μA and tens of mA) in which the exponential term n in the expression $I = Is \exp(qV/nkT)$ is rigorously 1 (within 0.5%). In this domain the epitaxial i layer operates under high injection but its contribution to the I–V characteristic is not essential[16] because the minority carrier concentration in this region is practically constant. The I–V dependence is governed by the p^+ region alone, which functions at low injection level and where the minority carrier concentration damps down to the equilibrium value. To prove this statement we will first derive the expression of the saturation current without taking notice of heavy-doping effects, and then proceed to an exhaustive treatment of the saturation current as affected by heavy-doping in the p^+ emitter.

Referring to the structure in Fig. 2, using Boltzmann statistics and neglecting high doping effects, one has the following expressions:

$$p = n_i \exp[-q(U - \phi_p)/kT]$$

$$n = n_i \exp[q(U - \phi_n)/kT] \tag{1}$$

$$Jn = -q\mu_n n \, \mathrm{d}U/\mathrm{d}x + qD_n \, \mathrm{d}n/\mathrm{d}x$$

$$= -q\mu_n n \, \mathrm{d}\phi_n/\mathrm{d}x. \tag{2}$$

Since in the $[-x_j, w - x_j]$ region $\mathrm{d}\phi_p/\mathrm{d}x = 0$, then $Jn\,p/qD_n = \mathrm{d}(pn)/\mathrm{d}x$ and integrating:

$$Jn = \frac{qn_i^2[\exp(qV/kT) - 1]}{\int_{-x_j}^{w-x_j} p(x)\,\mathrm{d}x/D_n(x)}. \tag{3}$$

If an average diffusion coefficient is defined as:

$$\bar{D}_n = \frac{\int_{-x_j}^{w-x_j} p(x)\,dx}{\int_{-x_j}^{w-x_j} p(x)\,dx/D_n(x)}, \tag{4}$$

the electron current can be written:

$$Jn = \frac{q\bar{D}_n n_i^2[\exp(qV/kT)-1]}{\int_{-x_j}^{w-x_j} p(x)\,dx}, \tag{5}$$

and, in a similar way, the hole current:

$$-Jp = \frac{q\bar{D}_p n_i^2[\exp(qV/kT)-1]}{\int_{-x_j}^{w-x_j} n(x)\,dx}, \tag{6}$$

eqns (5) and (6) can be recast as:

$$Jp = \frac{\text{const.}\ \bar{D}_p[\exp(qV/kT)-1]}{Q_{\text{inj}}(i)+Q_{\text{dop}}(n)}, \tag{7}$$

$$Jn = \frac{\text{const.}\ \bar{D}_n[\exp(qV/kT)-1]}{Q_{\text{inj}}(i)+Q_{\text{dop}}(p)}, \tag{8}$$

where $Q_{\text{inj}}(i)$ is the total charge injected in the base per unit area; $Q_{\text{dop}}(n)$ and $Q_{\text{dop}}(p)$ represent the majority carrier concentration per unit area in the heavily-doped regions of the device.

Due to the narrow base:

$$Q_{\text{dop}}(p), \quad Q_{\text{dop}}(n) \gg Q_{\text{inj}}(i), \tag{9}$$

and since the p diffused layer is much thinner than the diffusion length in the substrate:

$$q_{\text{dop}}(p) \ll Q_{\text{dop}}(n) = N_{\text{sub}} L_{\text{diff}}(n),$$

it follows that:

$$J_n \gg J_p, \tag{10}$$

and that the current is due to only one type of carriers—the electrons. This feature was first pointed out by Nayto and colleagues[17]. Using eqn (10), the I–V characteristic is recast as:

$$I = \frac{qn_i^2 A[\exp(qV/kT)-1]}{\int_{-x_j}^{0} p(x)\,dx/D_n(x)}. \tag{11}$$

Expression (11) underlines the fact that the value of the saturation current is set by the physics of the p^+ emitter alone. Accordingly, heavy-doping effects will be considered further only in this region. In addition, this endorses the experimental observation that the I–V characteristic has the ideal Shockley exponential form (with $n = 1$).

A conventional method[10] is used below to compute the saturation current starting from the general expression:

$$J_n = qD_n\,dn/dx - n\mu_n kT\,d[\ln(n^0)]/dx, \tag{12}$$

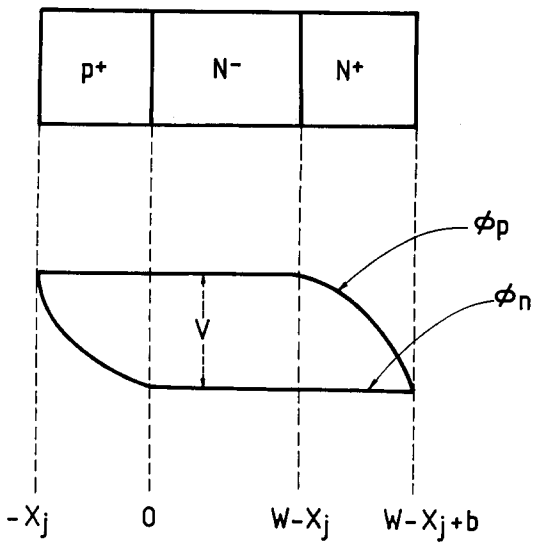

Fig. 2. The narrow base pin diode structure and the quasi-Fermi potential diagram used in the calculations of this paper.

in the p^+ emitter, where the minority carriers (electrons) still obey nondegenerate statistics (i.e. Boltzmann). Integrating eqn (12) with the reasonable assumptions:

$$J_n^0 = 0; \quad n = n' + n^0; \quad \mu_n = \mu_n^0 \tag{13}$$

superscript "0" depicts thermal equilibrium values,

$$J_n(0) = J_n = \text{constant (transparency assumed)} \tag{14}$$

$$n'(0) = n^0(0)[\exp(qV/kT)-1], \tag{15}$$

one gets:

$$\frac{n'(0)}{n^0(0)} = \int_{-x_j}^{0} \frac{J_n\,dx}{qD_n n^0(x)}. \tag{16}$$

Marshak and Van Vliet[10] have demonstrated that, as long as the space charge depletion region in the i layer is practically independent of the applied voltage (a condition always fulfilled in narrow base pin diodes which are punched-through), expression (15) is valid even in a junction with position-dependent bandgap.

Combining expressions (15) and (16) one gets the I–V characteristic eqn (17), whose form is remarkably like that given by eqn (11), arrived at in a different way.

$$I = \frac{qA[\exp(qV/kT)-1]}{\int_{-x_j}^{0} dx/D_n(x)n^0(x)}. \tag{17}$$

Heavy doping effects are twice present here through $D_n(x)$ and $n^0(x)$ but eqn (17) requires some

rearrangement to make them more evident. First, we employ the effective intrinsic concentration[5]:

$$n_{ie}^2 = n_i^2 \exp(\Delta Eg/kT)\mathscr{F}_{1/2}(m)/\exp(m) \tag{18}$$

where:

$$m(x) = [Ev(x) - E_F(x)]/kT, \tag{19}$$

and n_i is the intrinsic concentration in the Si base. After some simple algebra the *I–V* and *Is* are recast:

$$I = \frac{qn_i^2 A\,[\exp(qV/kT) - 1]}{\displaystyle\int_{x_j}^{0} Nv \exp[m(x)]\,dx \times /\{D_n(x)\exp[\Delta Eg(x)/kT]\}} \tag{20}$$

$$Is = \frac{qn_i^2 A}{\displaystyle\int_{-x_j}^{0} Nv \exp[m(x)]\,dx \times /\{D_n(x)\exp[\Delta Eg(x)/kT]\}} \tag{21}$$

$m(x)$ is computed from the generalized charge neutrality equation

$$\begin{aligned} &Na(x)/\{1 + 0.5\exp[(E_A(x) - E_F(x))/kT]\} \\ &\quad + Nc\exp[-(Ec(x) - E_F(x))/kT] \\ &= Nd(x)/\{1 + 2\exp[(E_F(x) - E_D(x))/kT]\} \\ &\quad + Nv\mathscr{F}_{1/2}([Ev(x) - E_F(x)]/kT), \end{aligned} \tag{22}$$

in which the doping profile $Na(x)$–$Nd(x)$ is considered arbitrary and position-dependent trap levels and bandgap (i.e. bandgap narrowing) are assumed. In the doping range of interest $|N(x)| < 1.5 \times 10^{20}\,\mathrm{cm}^{-3}$, a good approximation for the Fermi integral is provided by:

$$\mathscr{F}_{1/2}(m) = \exp(m)/[1 + 0.27\exp(m)]. \tag{23}$$

Using eqn (23) and neglecting $\exp(E_F - E_D) \ll 1$, equation (22) becomes a 3rd degree polynomial equation in $\exp(m)$, which is analytically solved with Cardan's formulae. (Detailed derivation for n^+ Si can be found in De Castro and Rudan's paper[18].)

For an accurate prediction of *Is*, and to make diode design possible, the position-dependent bandgap narrowing $\Delta Eg(x)$ and diffusion coefficient $D_n(x)$ must be precisely known. As minority carriers are nondegenerate, the Einstein relation $D_n = kT\mu/q$ still holds. However, recent experiments have revealed unequal majority and minority carrier mobilities $\mu_n^n \neq \mu_n^p$[16,17], casting uncertainty on currently accepted minority carrier mobility values. There are several empirical models[6,19], trying to monitor the mobility of holes in n^+ Si as minority carriers.

We have adapted Fossum *et al.*'s minority hole model[6] to describe the minority electron mobility. At room temperature it reduces with good approximation to (a complete model is given in the Appendix):

$$\mu_n^p = \mu_n^n \exp(-\alpha\Delta Eg/kT), \tag{24}$$

where α (unknown) is a fitting parameter to be determined from experiments and μ_n^n is the conventional, temperature and doping-dependent majority carrier mobility[20]. This model provided very good agreement with experimental data and appears to describe with reasonable accuracy the temperature dependence of hole mobility in n^+ Si. As introduced by Fossum *et al.*, the model could be used to determine the shift of the valance and conduction band profiles due to bandgap narrowing. However, it may be argued that these shifts are not identical to the notions of band offsets as defined from the electron affinity rule in heterojunction theory[11,21]. Furthermore, Fossum *et al.*'s is only a phenomenological model which has yet to be theoretically sustained. This should prove an interesting ground for future experimental and theoretical work. For the present, one can regard this mobility model as empirical, as all mobility models currently available.

For the bandgap narrowing the well-known formula derived by Slootboom for p^+ silicon has been employed:

$$\begin{aligned} \Delta Eg = 9E - 3\{&\ln[(Nd + Na)/10^{17}] \\ &+ (\ln^2[(Nd + Na)/10^{17}] + 0.5)^{1/2}\}\ \mathrm{eV}, \end{aligned} \tag{25}$$

because of its good agreement with recent bandgap calculations and measured data[5].

By replicating n^+ silicon data[22], the acceptor level-doping dependence $[E_A(N)]$ is monitored with the following empirical expression:

$$\begin{aligned} E_A(x) = 0.045 \\ - [0.01258[N(x)/No]^{1/3} + 0.0031]\mathrm{eV} \end{aligned} \tag{26}$$

where $No = 10^{18}\,\mathrm{cm}^{-3}$.

Expression (21), in a simpler form [$N(x)$ constant] was recommended for possible use in bandgap narrowing measurements [12]. It is pointed out here that such measurements can be misleading unless correct values for *Dn* are considered. Measuring *Is* will give the combined $D_n^p \exp(\Delta Eg/kT)$ product or, to be more specific: $(kT/q)\mu_n^n \exp[(1 - \alpha)\Delta Eg/kT]$, rather than the habitual $D_n^n \exp(\Delta Eg/kT)$. Consequently, as recently recognised[19], one needs yet another independent measurement to allow for the extraction of both the minority mobility and bandgap narrowing. Otherwise, as is the case of this paper, one of these two heavy-doping parameters has to be assumed *a priori* known.

2.4. *I–V model validity and limitations*

As previously stated, the most restrictive assumption in the model is the neglection of recombination in all device regions. To estimate the error introduced by such an approximation we have extended the saturation current expression to include the effect of recombination in the p^+ emitter, as developed by

Del Alamo and Swanson[7,23]. In this case, defining the effective Gummel factor as:

$$Geff(x) = \int_{-x}^{0} Nv \exp[m(x)]\,dx \times /\{D_n(x)\exp[\Delta Eg(x)/kT]\}, \quad (27)$$

the saturation current is recast to:

$$Is = \frac{qn_i^2 A\left\{1 + \int_{-x_j}^{0} n^0(x) \times [Geff(-x_j) - Geff(x)]\,dx/\tau_n(x)\right\}}{Geff(-x_j)} \quad (28)$$

where

$$1/\tau_n = 1/\tau_{n0} + C_p p^2$$

is the electron carrier lifetime in which Auger recombination ($C_p = 9 \times 10^{-32}$ cm^6/s, $\tau_{n0} = 5 \times 10^{-4}$ s)[24] is included.

Expression (28) (also known as the quasi-transparent approximation) differs from eqn (21) by the integral term in the numerator, hereafter called correction term, which represents the contribution due to recombination (mainly Auger type) in the heavily doped emitter. Numeric simulation of *npn* transistors[7,13,23] has revealed that the transparent model (21) undervalues while the quasi-transparent one overestimates the saturation current. Consequently, the maximum error introduced by eqn (21) is roughly half of the correction term and can be thus theoretically predicted. Figure 3 plots the correction term as a function of junction depth for diodes with Gaussian profiles and a fixed surface concentration 10^{20} cm^{-3}. The calculations have been performed for two sets of minority mobility values ($\alpha = 0$ i.e. majority carrier value and $\alpha = 0.35$) at 300 and 310 K. The diffusion coefficients as function of doping are presented in the bottom picture. The revised values are in reasonable agreement with those measured and computed for minority holes in n-type silicon[6]; the minority carrier mobility values are $5 \cdots 8$ times lower at heavy doping. One can easily notice that the range of validity of the transparent and quasi-transparent models is quite sensitive to temperature and mobility coefficients and that, for 1 μm junctions the error in the saturation current (attributed to recombination in the emitter), irrespective of mobility coefficient, is at most 20%. It must be specified at this point that Del Alamo and Swanson[7] define the quasi-transparent domain eqn (28) as the range of emitters in which bulk recombination is small enough so that the transparent electron (hole) distribution is only slightly perturbed. Consequently, the correction terms in excess of 50% obtained with the quasi-transparent model may be inaccurate. This problem will be reconsidered in a later section.

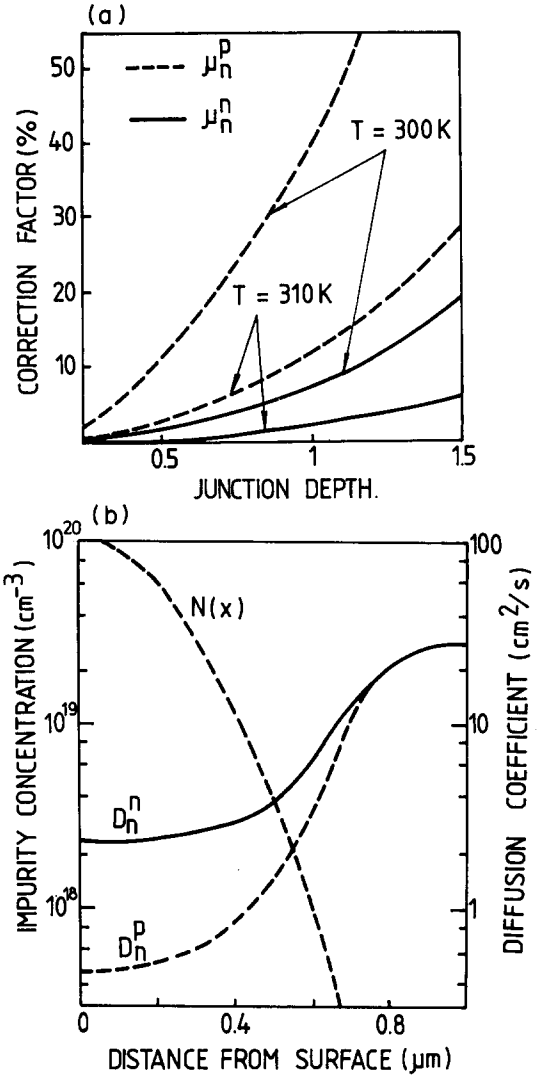

Fig. 3. (a) A comparison of the transparent and quasi-transparent emitter models for p^+ silicon as a function of junction depth, temperature and minority electron mobility model. The correction term represents the difference between the two models. (b) Minority electron diffusion coefficient as a function of distance from the surface for $\alpha = 0$ (usual majority electrons value) and $\alpha = 0.35$ (proposed model) is a 1 μm emitter diode. The impurity charge profile is also plotted.

3. PROPOSED MODEL FOR STORED CHARGE CALCULATION

The Qs–I characteristic is further derived, with heavy-doping effects included via the saturation current eqn (21). The influence of degeneracy and Auger recombination on minority carrier distribution in the base and stored charge is briefly evaluated.

3.1. Carrier distribution during the forward conduction period

We consider an impurity profile resulted from a shallow p^+ diffusion in a thin, low-doped epi-layer, associated with the out-diffusion from the n^+

substrate. Its form is for the moment arbitrary; $N(x)$. The p^+i junction is located in the origin and the surface is at $x = -x_j$ (Fig. 2).

In the forward conduction regime, at high injection levels in the base, due to quasineutrality and the practically constant quasi-Fermi levels, one has the following expressions:

$$p(x) - n(x) - N(x) = 0 \tag{29}$$

$$p(x) = p(0)\exp(-qU/kT) \tag{30}$$

$$n(x) = p(0)\exp(qU/kT) \tag{31}$$

in which $p(0)$ is the hole concentration at the junction ($p(0) = n(0)$) and U is the electric potential. Hence;

$$U = -(kT/q)\sinh^{-1}[N(x)/2p(0)] \tag{32}$$

$$E = (kT/q)\mathrm{d}/\mathrm{d}x\{\sinh^{-1}[N(x)/2p(0)]\} \tag{33}$$

$$p(x) = p(0)\exp\{\sinh^{-1}[N(x)/2p(0)]\}, \tag{34}$$

$$n(x) = p(0)\exp\{-\sinh^{-1}[N(x)/2p(0)]\}. \tag{35}$$

The stored charge is then derived as:

$$Qs = qA\left[\int_{-x_j}^{0} n(x)\,\mathrm{d}x + \int_{0}^{w-x_j} p(x)\,\mathrm{d}x\right], \tag{36}$$

where A is the diode area and w is the thickness of the epitaxial layer. The problem is fully solved if the junction carrier concentration $p(0)$ is determined. Since the i layer operates in the high injection regime, one has:

$$p(0)^2 = n(0)^2 = n_i^2\exp(qV/kT). \tag{37}$$

Expression (37) gives $p(0)$ as a function of the terminal voltage and, since with good approximation:

$$i = Is\exp(qV/kT), \tag{38}$$

the $p(0) - I$ dependence is obtained:

$$p(0) = n_i(I/Is)^{1/2}. \tag{39}$$

Heavy-doping effects are included in the expression of the junction carrier concentration $p(0)$ via the saturation current Is. A more thorough derivation would also require the alteration of (29) to account for heavy-doping and deionization effects. Such a modification renders an analytic approach improbable and is conducive to an insignificant improvement in accuracy. Finally, the stored charge expression is recast by combination of eqns (22)–(24) and (39):

$$Qs = qn_iA(I/Is)^{1/2} \times \left\{\int_{-x_j}^{0} \exp[\sinh^{-1}(0.5\,N/n_i(I/Is)^{1/2})]\mathrm{d}x + \int_{0}^{w-x_j} \exp[-\sinh^{-1}(0.5\,N/n_i(I/Is)^{1/2}]\,\mathrm{d}x\right\}. \tag{40}$$

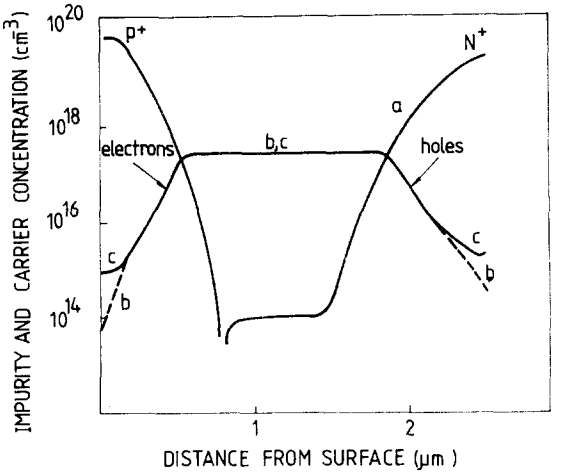

Fig. 4. Comparison between Kurata's large signal numeric analysis results and our results for the "standard profile": (a) Kurata's standard profile; (b) Kurata's numerically calculated carrier distribution ($I_F = 20$ mA); (c) our results. Qs (Kurata) = 592 pC; Qs (present work) = 629 pC.

3.2. Validity of the stored charge model

In what regards the estimation of the stored charge, eqns (34) and (35) are strictly valid only in the base $[N(x) \ll 2p(0)]$ but they still offer an excellent approximation for the minority carrier concentration in the highly doped zones of the device, excepting very narrow regions near the surface and the epi-layer/substrate interface. The low minority carrier concentration in these regions brings a minor contribution to the overall charge. To prove it, Fig. 4 presents a comparison between Kurata's large signal numeric analysis[16] (which includes recombination throughout the diode) and present calculations. In our case, the carrier profiles are computed from eqns (34) and (35) and $p(0)$ was determined from Kurata's carrier distribution. Again, Kurata's $p(0)$ was used to compute the stored charge [with eqns (34), (35) and (36)] and the latter was compared with Kurata's value ($Qs = I_R\tau s$). The agreement is within 6% and matches the error predicted in Fig. 3 when majority carrier mobility values are assumed in the model. This confirms the assumption that the stored charge is independent on carrier lifetime in the narrow base.

The neglection of heavy-doping effects in the base is justified by the moderate concentration of injected carriers (at most $10^{18}\,\mathrm{cm}^{-3}$ at bias currents up to 20 mA) rendering Auger recombination and many-body effects insignificant. These effects should be important at higher current values, especially in small area diodes.

In this stored charge model heavy-doping effects are partially present through Is. Because of the square-root dependence of the stored charge on saturation current, the errors involved in the estimation of the latter are, as a rule, halved in the Qs–I characteristic.

Table 1. Physical parameters of analysed diodes

Diode type	N_0 (cm^{-3})	N_B (cm^{-3})	N_1 (cm^{-3})	x_j (μm)	W (μm)	D^* (μm)
S-band SRD	1×10^{20}	2.4×10^{14}	5.5×10^{19}	1	2.7	194
X-band SRD	1×10^{20}	2.4×10^{14}	3.8×10^{19}	1.2	3.0	76
K-band SRD	1×10^{20}	2.5×10^{14}	5×10^{19}	1.5	2.2	21
Test diode	9×10^{19}	1×10^{14}	5×10^{19}	0.35	1	252

D^* is the diameter of the junction.

4. EXPERIMENTAL

To verify the theory, three types of currently available step-recovery narrow base pin diodes were manufactured using thermal oxide mesa technology. The diodes are mounted in F-27 D Thomson CSF-type microwave case. An additional shallow-implanted junction ($x_j = 0.35\ \mu$m) was fabricated to avoid the influence of emitter recombination on the accuracy of minority mobility measurements.

The impurity profile parameters are summarized in Table 1. The profile is assumed Gaussian and described by expression (41) in which the redistribution from the substrate is also accounted for.

$$N(x) = N_0 \exp[-(x + x_j)^2/a^2] - N_B - N_1/2\{\exp[-(w - x_j - x)^2/b^2]\}, \quad (41)$$

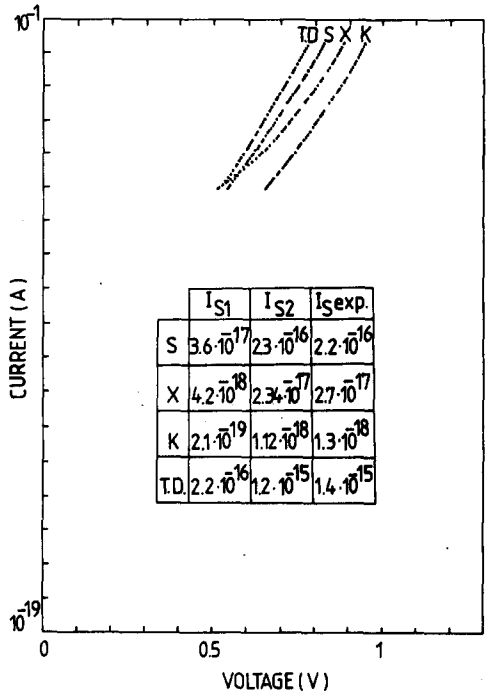

Fig. 5. Measured I–V characteristic for S, X and K band devices analysed in this paper. I_{S1} calculated values for the saturation current neglecting heavy-doping effects. I_{S2} calculated values for the saturation current with full inclusion of the heavy-doping effects with $\alpha = 0.33$. I_S exp experimental values of the saturation current extrapolated from the I–V characteristics in the regions where the diode nonideality factor n is 1.

N_0, N_B and N_1 are the surface, i- and substrate layer concentrations, respectively. Because of the fabrication conditions $b = a/3$.

The saturation current was determined by a least squares fitting of the I–V characteristics (Fig. 5) in the extended Shockley domain, accurately measured with a Keithly-616 electrometer. The stored charge was measured in the experimental set-up presented in Fig. 6. To insure good precision, the magnitude of the reverse pulse was chosen so that $I_R > 10\ I_F$. The value of the stored charge is deducted from the area below the current pulse on the oscilloscope CRT display

$$\left(Qs = \int I_R\, d\tau\right).$$

5. RESULTS AND DISCUSSIONS

The measured and computed values of the saturation current for the four experimental profiles are included in the insert of Fig. 5. Two values of the calculated saturation current are presented. The first was obtained with eqn (11), neglecting heavy doping phenomena's effects, while the second was calculated from eqn (21) with full inclusion of heavy doping phenomena. The latter value is within an acceptable error (below 12%) of the measured saturation current if $\alpha = 0.33$ is assumed. The errors in the saturation current are also due to measurement uncertainties and lack of the precise knowledge of the actual doping profiles (which in the present case are obtained from N_1, N_0, w and x_j measurements only).

If high doping effects are neglected, the saturation current is underestimated by nearly one order of magnitude. Also, should the majority carrier- instead of the minority carrier diffusion coefficient be employed (i.e. $\alpha = 0$), the computed saturation current is $4 \cdots 5$ times above the measured value (Fig. 5).

The surprising feature revealed by the saturation current measurements is the fact that the error

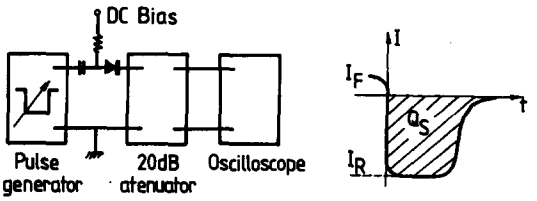

Fig. 6. Experimental set-up for stored charge measurements.

between theory (transparent model) and experiment even for diodes with junction depths of 1.5 μm, is lower than the theoretically predicted one. The theoretically estimated accuracy of eqns (21) and (28) is linearly dependent on the electron Auger coefficient C_p, which has a fairly unreliable value. As recent measurements have evidenced lower than previously surmised C_n values, a similar trend might involve C_p, thus improving the accuracy and validity range of the present model and offering a possible explanation for the excellent agreement between our transparent-emitter model and experiment. Such a supposition is also supported by the much poorer performance of the quasi-transparent model for the 1.5 μm junction diode. It may be argued that the quasi-transparent model can be brought in agreement with the experiment if a larger value for $\alpha(\alpha = 0.4 \cdots 0.5)$ is considered. This, in turn, will lead to a prevailing recombination term in eqn (28), in contradiction with the initial assumption in the derivation of the quasi-transparent model and, consequently, the whole quasi-transparent emitter model breaks down. The contradiction is suppressed for values of C_p 3 to 4 times lower than the present ones. In this case both models give similar results for junction depths of up to 1.5 μm.

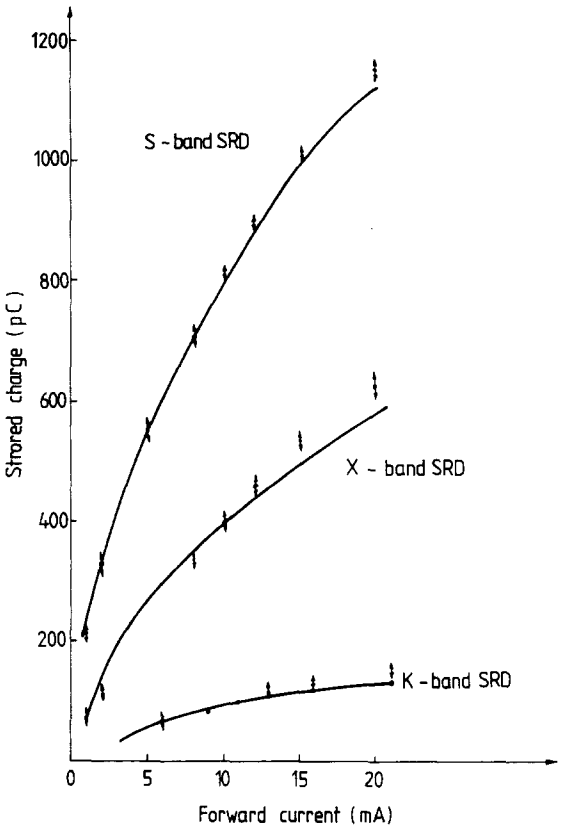

Fig. 7. Comparison between theoretical and experimental results for the variation of the stored charge vs forward current for S, X and K band devices.

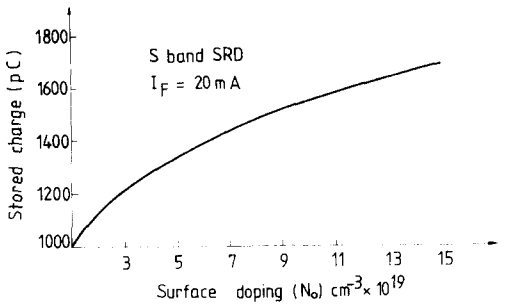

Fig. 8. Influence of the surface concentration in the p^+ region on the switching behaviour of narrow base pin diodes (computed results).

The stored charge was computed using the transparent model of the saturation current for all three types of diodes. Figure 7 summarizes the experimental and calculated results on the Qs–I dependence. The error (below 8%) is within the measurement uncertainty and theoretical predictions. The important conclusion to be drawn from the stored charge characteristic is its predictable behaviour. The stored charge and its dependence on the diode current lend themselves to accurate design. Such a design was performed by applying nonlinear optimization techniques based on an original pattern-search type algorithm. The optimization process allows for the alteration of device parameters (N_0, N_1, X_j, N_B and area) to better fit a desired Qs–I curve.

Dwelling further on the Qs–I plots of Fig. 7, one can notice that the error between theory and experiment tends to grow for higher frequency diodes. This may be explained by the increasing effect of recombination in the emitter (due to greater junction depth), the onset of many-body effects in the base and by the less accurate modelling of minority charge in the heavily doped regions [expressions (34) and (35)]. In these diodes the undoped region is thinner and the contribution of the heavily doped p and n layers to the overall charge is no longer negligible. For these diodes the present model underestimates stored charge. The error between theory and experiments does not exceed 10% and should be acceptable in most designs up to the K band.

The results of this study have been employed in an improved design of narrow-base pin diodes. Several design guidelines are resumed below.

The computations have indicated that the reduction of the surface concentration N_0 of the p^+ diffusion layer leads to a significant lowering of the stored charge. Figure 8 presents the variation of the stored charge with surface concentration and p^+ zone length. This behaviour underlines the importance of the stored charge located in the p^+ layer and suggests an ultimate optimization of the switching speed[25]. In fast switching pin diodes, a reduction of N_0 from 10^{20} cm^{-3} to 2–3 $\times$ 10^{19} cm^{-3} is conducive to a 50–70% increase in switching speed. In contrast, narrow base pin diodes designed to operate as

step-recovery devices require very high surface doping to maximise the value of Qs. Changing N_0 has practically no influence on other parameters central to device performance (i.e. breakdown voltage, transition time and capacitance), as opposed to alterations of other doping parameters such as w and a.

6. FINAL COMMENTS

A simple relationship between the stored charge and the impurity profile of narrow base pin diodes was derived. In order to obtain the dependence of the stored charge on the diode forward current, the modelling of the I–V characteristic of narrow base pin diodes has been revisited and heavy doping effects have been considered for the first time in such devices.

Experimental measurements performed on four sets of diodes with different profiles have evidenced errors less than 10% and 8%, respectively, for theoretically predicted Is and Qs values. These encouraging results have allowed for novel, provisional values of minority diffusion coefficients in heavily doped p^+ Si. Additional measurements on a wider range of impurity profiles and junction temperatures are required to validate these data which can facilitate the development of a reliable and self-contained set of heavy-doping related parameters (bandgap, mobility and Auger coefficients).

Acknowledgements—The authors wish to thank the anonymous reviewers whose pertinent remarks have helped reshape this paper.

REFERENCES

1. H. Benda and A. Spenke, *Proc. IEEE* **55,** 1131 (1967).
2. F. Berz, *Solid-St. Electron.* **22,** 967 (1979).
3. I. L. Moll, L. Krakauer and R. Shen, *Proc. IRE* **50,** 43 (1962).
4. J. W. Slotboom and H. C. De Graaff, *Solid-St. Electron.* **19,** 857 (1976).
5. S. R. Dhariwal, V. N. Ojha and G. P. Srivastava, *IEEE Trans. Electron Devices* **ED-32,** 44 (1985).
6. J. G. Fossum, D. E. Burk and S.-Y. Yung, *IEEE Trans. Electron Devices* **ED-32,** 1174 (1985).
7. J. A. Del Alamo and R. M. Swanson, *IEEE Trans. Electron Devices* **ED-31,** 1878 (1984).
8. A. H. Marshak and R. Shrivastava, *Solid-St. Electron.* **22,** 567 (1978).
9. K. M. Van Vliet and A. H. Marshak, *Solid-St. Electron.* **23,** 4 (1980).
10. A. H. Marshak and C. M. Van Vliet, *Proc. IEEE* **72,** 148 (1984).
11. M. S. Lundstrom and R. J. Schulke, *IEEE Trans. Electron Devices* **ED-30** 1151 (1983).
12. R. P. Mertens, H. J. DeMan and R. J. Van Overstraeten, *IEEE Trans. Electron Devices* **ED-20,** 772 (1973).
13. J.-S. Park, A. Neugroschel and F. A. Lindholm, *IEEE Trans. Electron Devices* **ED-33,** 240 (1986).
14. A. Neugroschel and F. A. Lindholm, *Appl. Phys. Lett.* **42,** 176 (1983).
15. D. D. Tang, F. F. Fang, M. Scheuermann and T. C. Chen, *Appl. Phys. Lett.* **49,** 150 (1986).
16. M. Kurata, *IEEE Trans. Electron Devices* **ED-19,** 735 (1973).
17. M. Naito, H. Mazuzaky and T. Ogawa, *IEEE Trans. Electron Devices* **ED-23,** 945 (1976).
18. E. de Castro and M. Rudan, *IEEE Trans. Electron Devices* **ED-31,** 785 (1983).
19. W. Kuzmicz and W. Zagozdzon-Wosik, *Solid-St. Electron.* **31,** 911 (1988).
20. N. D. Arora, J. R. Hauser and D. J. Roulston, *IEEE Trans. Electron Devices* **ED-29,** 292 (1982).
21. S. Voinigescu, *Int. J. Electron.* In press.
22. G. D. Mahan, *J. appl. Phys.* **51,** 2634 (1980).
23. J. A. Del Alamo and R. M. Swanson, *IEEE Trans. Electron Devices*, **ED-34,** 455 (1987).
24. J. Dziewior and W. Schmid, *Appl. Phys. Lett.* **31,** 346 (1977).
25. A. Müller and V. Buiculescu, *Proc. of the 7th Colloquim on Microwave Communication*, Budapest, p. 821 (1982).

APPENDIX

The present minority electron mobility model is a straight-forward adaptation of Fossum *et al.*'s formalism for minority holes in n^+ silicon[6] in which hopping conduction in band tails is accounted for.

$$\mu_n^p = (1 - \exp(-\Delta Ec/kT))\mu_{n(\text{hop})} + \exp(-\Delta Ec/kT)\mu_n^n. \quad \text{(A.1)}$$

In the above reference, the effect of the band tails is included by assuming "an effective rigid parabolic valence-band shift" which is replaced here by the corresponding ΔEc. Obviously, ΔEv and ΔEc are part of the bandgap narrowing ΔEg, but there is as yet no theoretical support to identify these band shifts with the valence and conduction band offsets, as defined from electron affinity rule. As a consequence, we have replaced ΔEc in equation (A.1) (to avoid any confusion with band offsets) with $\alpha\Delta$Eg. This can be justified by the fact that the shift in the conduction band has to be dependent on the bandgap narrowing. There is presently no need to use a more complicated dependence (i.e. α to be temperature dependent) until full sets of measurements in a wide temperature range are performed. Since the current measurements have been performed at a carefully controlled, fixed temperature, one parameter, α, is sufficient to match the experiments and model the electron mobility, and it has proven to provide very good match between measured and computed saturation current values. Furthermore, the mobility values obtained with this phenomenological model appear to be in good agreement with those recently measured in moderately-doped p Si[17] and to follow the trend of minority holes in n^+ Si[6,19] (i.e. values up to an order of magnitude lower than those of the majority hole ones).

Since $\mu_{n(\text{hop})}$ is very small compared to μ_n^n, expression (A1) reduces at room temperature to:

$$\mu_n^p = \exp(-\alpha\Delta Eg/kT)\mu_n^n. \quad \text{(A.2)}$$