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Letter

Stacked PIN diode structures for microwave switching

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Abstract

A diode structure consisting of several stacked PIN diodes with tunnel junctions serving as quasi-Ohmic intercontacts is proposed. This structure is preferable if a microwave switch is required to have both high breakdown voltage and very small switching time. In this case a conventional (single-base) PIN switch has too large forward voltage drop across the base at sufficiently high current densities, because the base length is much greater than the bipolar diffusion length. This leads to high electric fields in the base and the development of unwelcome hot-electron effects. The replacement of the long base with several narrow bases connected in series by heavily doped p^+n^+ tunnel inserts solves this problem effectively. Direct numerical calculations have shown that this stacked structure exhibits a substantially smaller DC forward voltage drop at the same switching times (or substantially smaller switching times at the same DC forward voltage drops). At the microwave frequency range, the resistance of the stacked structure can be decreased drastically because all the newly formed *pn*-junctions are shorted by their large capacitances. © 1999 Elsevier Science Ltd. All rights reserved.

PIN diodes are extensively used in microwave circuits because they can control the magnitude and phase of large microwave signals with high speed and efficiency. Their major applications are phase shifters, attenuators, and switches [1]. In this paper, we propose a novel design of PIN diodes that can be used for switching applications.

Among the basic requirements a microwave switch should satisfy, the most important are: (1) high breakdown voltage U_B (up to 1 kV, see Chang's book [2]), (2) high speed of operation, i.e. small switching times τ, (3) low DC forward voltage drop at high current densities, and (4) small AC resistance R_d of the base.

The first requirement is met only if the base is sufficiently long. Assuming the base doping to be so light that the avalanche breakdown takes place when the base is punched through and the electric field in it is nearly homogeneous, we can estimate the breakdown voltage as $U_B = E_B W$, where E_B is the breakdown field of a specific material and W is the base length. This punch-through regime is the most favorable for obtaining the highest value of U_B for a given W.

Small switching times of a PIN diode can be obtained if the lifetime of nonequilibrium carriers τ_0 in the base is also small [2]. However, this inevitably leads to a small bipolar diffusion length $L = \sqrt{D\tau_0}$, i.e. to a large forward voltage drop V_b across the base which at high injection levels is given by

$$V_b \simeq \frac{\pi}{2}\frac{D}{\mu_p + \mu_n}(b^{1/2} + b^{-1/2})\exp\left\{\frac{W}{2L}\right\}, \tag{1}$$

for $\exp\{(W/2L)\} \gg b,\ b^{-1}$. Here $D = 2D_pD_n/(D_p + D_n)$ is the bipolar diffusion coefficient, D_p and D_n are the diffusion coefficients of electrons and holes respect-

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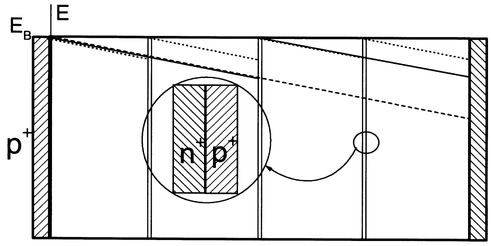

Fig. 1. Idealized distributions of the electric field in single- (dashed line), two- (solid line) and four- (dotted line) base diodes at their breakdown voltages. The structure of the tunnel interconnection are presented in the insert.

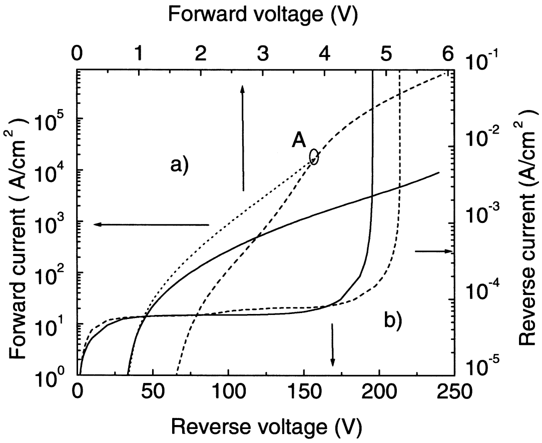

Fig. 2. *IV*-characteristics of InP diode structures. (a) Forward characteristics of the single-base (solid line) and double (dashed line) structures for $\tau_0 = 0.1$ ns, and the single structure for $\tau_0 = 0.2$ ns (dotted line). (b) Reverse characteristics of the single (solid line) and double (dashed line) structures.

ively, and $b = \mu_n/\mu_p$ is the ratio of the electron (μ_n) and hole (μ_p) mobilities.

Thus, we see that simultaneous meeting the first two requirements contradicts to the third one. Besides, the voltage across the base actually drops only across its relatively short portion in the vicinity of the minimum concentration of injected carriers. Since the length of that portion is about (1–2)L, the maximum electric field in the base can be estimated as $E_{max} \simeq V_b/L$. This means that at small L, E_{max} becomes very high, which leads to unwelcome hot-electron effects [3–5].

To overcome these problems, we propose a new structure consisting of several stacked PIN diodes. The distribution of the electric field for the breakdown voltages U_{B1}, U_{B2}, and U_{B4} for one-, two-, and four-base structures, respectively, is presented in Fig. 1. The bases in these structures are separated with thin n^+p^+ double layers whose structure is shown in the insert in Fig. 1. It is seen that if the bases are equally doped and the total length remains constant, i.e. $W_1 = 2W_2 = 4W_4$, we always have $U_{B4} > U_{B2} > U_{B1}$, the inequalities being stronger for heavier doping. The embedded n^+p^+ connection layers provide sufficient injection level so that the inner p^+in^+-diodes could operate independently. Besides, a tunnel n^+p^+-junction exist inside each connection layer. These tunnel junctions are reverse biased and serve as quasi-Ohmic contacts when the p^+in^+-diodes are forward biased.

Such a procedure leads to the following: (1) the breakdown voltage remains unchanged or becomes even higher and (2) the forward voltage drop across each shorter base and, consequently, the maximum electric field decreases drastically at the same τ_0 (see Eq. (1)). This means that for certain given values of U_B and τ_0, a PIN diode can not be designed as a single-base structure due to the hot-electron effects. Instead, it should be designed as a vertically stacked multibase structure where these effects disappear.

Obviously, such a structure can be put into practice if the entire device is grown layer-by-layer with the use of MOCVD or MBE. The major problem in the design of such devices is how to obtain connective tunnel junctions which would have a sufficiently low resistance. One of the most promising methods here is to use tunnel $p^{++}n^{++}$-heterojunctions, i.e. to embed a thin narrow-band-gap layer, in which the probability of the Zener tunneling is much higher, into the depletion region of a conventional tunnel junction. This method is being extensively applied by N. Holonyak and coauthors who use $In_{0.10}Ga_{0.90}As$ layers with a thickness of about 100 Å as tunnel enhancement layers (TELs) in their laser devices [6–9]. The value of $R_T = 3 \times 10^{-5}$ Ωcm^2 for GaAs tunnel junction with $In_{0.15}Ga_{0.85}As$ TEL [10] is, probably, a record experimental value for the resistance of tunnel junctions at small reverse bias voltages. However, in our case where the current $J_f = 10^4$–10^5 A/cm^2, the conductivity is expected to be higher due to the nonlinearity of the reverse *IV*-characteristics of tunnel junctions.

Tunnel-junction interconnected structures were also used in the design of solar cells tandems and multiple junction cells [11,12]. There are propositions to use them in the design of power diodes [13] and VCSELs [14].

The proposed design leads to additional DC forward voltage drops of about nJ_fR_T across the tunnel contacts and of about nE_g across the newly-formed p^+i- or n^+i-junctions. Here n is the number of interconnections, E_g is the band gap. Therefore, the use of the stacked diodes is justified if n is not too large and the current is sufficiently high so that the voltage drops mostly across the bases. However, at the microwave frequency range where the resistance of the diode R_d is determined by the AC voltage drop across the base only [15–17], the tunnel junctions as well as the p^+i-

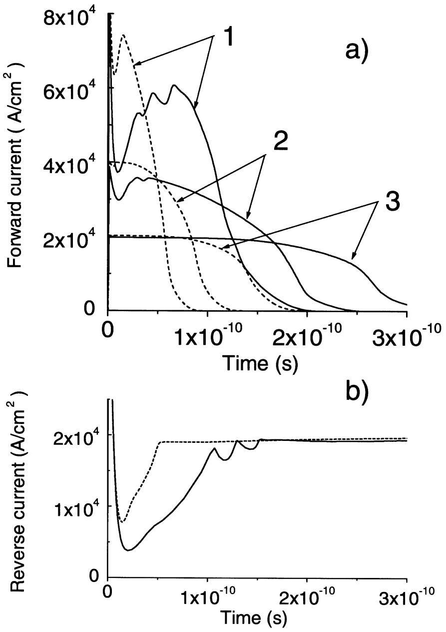

Fig. 3. Transient characteristics of InP single (solid line) and double (dashed line) diode structures. (a) Reverse current density vs time for switching the structures off at different R_0. $I_0=V_0/R_0=6\times10^4$ A/cm^2 (1), 4×10^4 A/cm^2 (2) and 2×10^4 A/cm^2 (3). (b) Forward current density vs time for switching the structures on at $R_0=2.5\times10^{-3}$ Ωcm^2.

or n^+i-junctions are shorted by their large capacitances [18] and, therefore, n can be large.

To illustrate the proposed approach we have performed direct numerical simulations. The most widespread materials for the design and fabrication of microwave switches are GaAs, InGaAs, and InP. As the required τ decreases and V_B increases, InP should be preferred because of its large electron drift velocity peak electric field [19] $E_c\simeq11$ kV/cm at which the hot-electron effects become strongly pronounced. For this material, the TELs in p^+n^+-tunnel junctions can be grown of $In_{0.53}Ga_{0.47}As$.

In Fig. 2b reverse IV-characteristics for a conventional InP PIN diode with the base length of 6 μm (solid line) and for a double structure with the base lengths of 3 μm each (dashed line) are presented. The doping concentrations are 10^{19} cm^{-3} in all the 0.5-μm-length p^+- and n^+-emitters and 10^{15} cm^{-3} in all the bases. For these parameters, the breakdown voltage of the structures is about 200 V. We have used the values of impact ionization coefficients $\alpha_{p,n}$ (E) given by Stillman et al. [20].

Forward IV-characteristics of these structures are presented in Fig. 2a. We have chosen the lifetime τ_0 in the structures to be 0.1 ns and the values of electron and hole low-field mobilities to be $\mu_n=500$ cm^2/Vs, $\mu_p=50$ cm^2/Vs in the emitters and $\mu_n=4600$ cm^2/Vs, $\mu_p=150$ cm^2/Vs in the bases. It is seen that at $V_f=6$ V, the current density in the double structure is almost two orders of magnitude higher than that in the conventional diode. This means that the former's value of R_d which is inversely proportional to the current [18] is two orders of magnitude smaller. To compensate this difference, we have to take $\tau_0=0.2$ ns in the single structure so that the two structures had the same $V_f=3.9$ V at the current of 2×10^4 A/cm^2 (point A at Fig. 2a).

To demonstrate a difference in switching times, we have performed nonstationary simulations of switching the two structures off (Fig. 3a) at three different load resistances R_0 and for switching them on (Fig. 3b). The forward current in the 'on' state is 2×10^4 A/cm^2, the reverse voltage in the 'off' state is $V_0=100$ V. It is seen that the double structure yields an approximately two-fold gain in switching time. Besides, the single structure exhibits well pronounced transient oscillations due to the development of hot-electron effects that lead to an additional elongation of the transient processes especially at large current densities (see Fig. 3a).

For our numerical calculations, we have used the device simulator 'ATLAS' [21] that solves the drift–diffusion problem together with the Poisson's equation. The tunnel junctions have been modeled by introducing a tunnel generation term depending on the electric field into the continuity equation. This simulator also allows us to take into account hot-electron effects in the bases by considering electron and hole mobilities local functions of the electric field. We have chosen the functions that fit the experimental data on the electron and hole drift velocities vs electric field [19]. The diffusion coefficients are recalculated according to the Einstein's relation at the room temperature. Of course, this is not a rigorous procedure, however, our results are aimed at specifying regimes of the device operation where the hot-electron effects become essential rather than their exact description.

As a conclusion, we have described and simulated numerically a stacked PIN diode structure for microwave switching. This structure allows a higher speed of operation than that in a conventional PIN diode at the same breakdown voltage and DC forward voltage drop and current density. We would like to emphasize that if a switch is supposed to operate in a pulsed regime, the forward DC voltage drop is no longer a critical parameter. Then, since all the pn-junctions at microwave frequencies are shorted by their large capacitances, the number of stacked diodes might be however large to provide for the smallest R_d. In this case, a gain in speed of operation will be much more impressive.

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