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Peculiarities of Reverse Current–Voltage Characteristics of GaAs Lo–Hi–Lo Impatt Diodes

By

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In the current–voltage (I–V) characteristics of Schottky-barrier GaAs diodes having a complex doping profile in the base regions of n–n$^+$–n type a strong current–voltage dependence is observed in the prebreakdown region. Breaks are found to appear in these regions when with increasing V a sharp decrease of the differential conductivity dI/dV at a certain $V = V_c$ occurs. The tunnel currents in such structures are calculated. It is shown that the sharpest dI/dV decrease is caused by the spiking of the highly doped n$^+$-region, while the transition from the thermofield tunneling (maximum contribution to tunnelling current caused by carriers with an energy above the Fermi level in the metal) to the field tunneling (current maximum caused by carriers with an energy at the Fermi level) yields a less sharp change in dI/dV. The higher the concentration in the n$^+$-region, the greater are the tunnel currents. The greater the doping differences in the n$^+$- and n-regions the more distinct are the breaks. The dependences of V_c and the I–V-characteristics on doping strength and thickness of each of the regions of the n–n$^+$–n diode are determined.

На вольтамперных характеристиках (ВАХ) арсенидгаллиевых диодов с барьером Шоттки, имеющих сложный профиль легирования в базе типа n–n$^+$–n, наблюдались участки с сильной зависимостью тока I от напряжения V в предпробойной области. Причем на самих этих участках наблюдались изломы, когда с ростом V происходит резкое уменьшение дифференциальной проводимости dI/dV при некотором $V = V_c$. Рассчитаны туннельные токи в таких структурах и показано, что наиболее резкое уменьшение dI/dV происходит при проколе сильнолегированной n$^+$-области, а вторая причина — переход от термополевого туннелирования, когда максимум туннельного тока обусловлен носителями с энергией выше уровня ферми в металле, к полевому туннелированию, когда он находится на уровне ферми — дает менее резкое изменение наклона. Туннельные токи тем больше, чем выше концентрация в n$^+$-области, а изломы выражены четче при большем различии в легировании n$^+$ и n областей. Определены зависимости V_c и ВАХ от уровней легирования и размеров каждой из областей n–n$^+$n диода.

1. Introduction

When measuring the reverse I–V characteristics of the Schottky-barrier Lo–Hi–Lo diodes regions were observed with a strong current (I)–voltage (V) dependence in the prebreakdown region. Breaks were found to appear in these region when with increasing V there occurs a sharp decrease of the differential conductivity dI/dV at $V = V_c$. Usually it is assumed that the field currents in highly doped homogeneous Schottky diodes are caused by electron tunneling from the metal into the semiconductor (see, for example, [1, 2]). Analogous models were used for the Hi–Lo structures in [3]. We calculated the tunnel currents for the Lo–Hi–Lo structures in order to investigate if the observed peculiarities in the "field" regions of reverse I–V characteristics can be explained in the framework of this model. The general expression for the tunnel current

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density obtained in the quasi-classical approach was used (see, for example, [2])

$$j = -A \int_{E_1}^{E_2} D \, \mathrm{d}E_x \,, \qquad D = \ln B \cdot \exp \left(-\alpha \int_{x_1}^{x_2} \sqrt{U(x) - E_x} \, \mathrm{d}x\right) , \tag{1}$$

where

$$A = \frac{4\pi m_{\mathrm{M}} e k_0 T}{h^3} , \qquad \alpha = \frac{2\sqrt{2m_s}}{\hbar} , \qquad B = \frac{1 + \exp\left[(\zeta_{\mathrm{m}} - E_x)/k_0 T\right]}{1 + \exp\left[(\zeta_{\mathrm{m}} - E_x - U_{\mathrm{m}})/k_0 T\right]} . \tag{2}$$

m_{M} and m_s are the electron effective masses in metal and semiconductor, respectively, T is the temperature, k_0 the Boltzmann constant, $E_1 = \Delta + \zeta_{\mathrm{m}} - U_{\mathrm{n}}$ at $U_{\mathrm{n}} < \Delta + \zeta_{\mathrm{m}}$ and $E_1 = 0$ at $U_{\mathrm{n}} > \Delta + \zeta_{\mathrm{m}}$, $E_2 = U_0 = eV_0 + \Delta + \zeta_{\mathrm{m}}$, E_x is the kinetic energy of the electron in x-direction, $V(x)$ the potential energy in point x. The potential

$$\Phi(x) = \frac{U(x) - \zeta_{\mathrm{m}} - \Delta + eV}{k_0 T} \tag{3}$$

which is used below, is selected in such a way that it vanishes far in the bulk of the semiconductor and reaches its maximum $\Phi_0 = e(V_0 + V)/k_0 T$ near the metal–semiconductor interface. The notation of ζ_{m}, U_0, U_{n}, Δ are seen from Fig. 1a, x_1 and x_2 being classic turning points.

2. Numerical Calculations

By means of numerical integration we calculated the dependence of the current density j on the applied reverse bias V for four temperatures $T = 300$, 225, 150, 75 K in the Lo–Hi–Lo GaAs Schottky diodes ($m_s = 0.067 m_0$, m_0 is the free electron mass). The $V(x)$ dependence necessary for the calculation of current from (1) was determined for the Lo–Hi–Lo structures given in Fig. 1a from the Poisson equation, the image forces being neglected. The results of the calculations are given in the Appendix.

The following parameters of the Schottky diodes were chosen: $eV_0 = 0.9$ eV; $\zeta_{\mathrm{m}} = 0.1$ eV; $\Delta = 0.01$ eV. Doping in each of n and n$^+$ regions was accepted to be uniform with $N_1 = N_3 = 2 \times 10^{15}$ cm^{-3}, $N_2 = 5 \times 10^{16}$ cm^{-3}, the boundaries between the regions were sharply pointed (Fig. 1 b). The thickness of the second LO region Δd_3 was selected to be large in order to prevent spiking of the structure in the whole range of the bias $V = 1$ to 50 V, i.e. the width of the depletion region was less than the thickness of the semiconductor d_3 (Fig. 1). The thickness of regions 1 and 2 were varied and

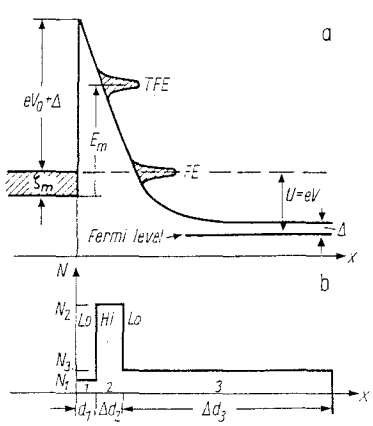

Fig. 1. a) The potential energy of the electron in the Schottky barrier as a function of x at reverse bias and b) the dependence of the donor concentration N on the coordinate x in the Lo–Hi–Lo structure

the currents were calculated for 15 structures from the sets $d_1 = 0.05$, 0.12, 0.25, 0.5 μm and $d_2 = 0.12$, 0.25, 0.5 μm. Note that the thickness and the doping of the first regions are chosen in such a way that the region is spiked before the bias is applied. The electrons with energy states lying deeply under the Fermi level of the metal do not contribute to the tunnel current. In order to avoid the integration over the region which does not contribute to (1), the value of ζ_m was selected one order of magnitude smaller than the real ζ_m for the metals. The validity of such a substitution for the investigations performed is seen from Fig. 3 discussed below.

3. Results and Their Discussion

Fig. 2 presents the calculated dependences $j(V)$. It is seen that the curves belonging to one and the same temperature for structures with the same Δd_2 are grouped very distinctly, but the dependence on the thickness d_1 is expressed less weakly. The influence of the latter is increased with the decrease of T and V.

Another typical feature is the break in the I–V characteristics, caused by the spiking of the Hi region. At $V < V_c(j_c)$ the Hi region is not spiked and due to the high doping of this region the small V increases result in the strong narrowing of the barrier width. At $V > V_c(j_c)$ the voltage drops mainly on the second Lo region, with V growing the barrier is weakly narrowing. Because of this fact at $V = V_c(j_c)$ the differential conductivity sharply decreases. The break is shown in Fig. 2 by arrows, and for a given temperature it occurs at one and the same current j_c in diodes with identical dimensions of the Hi region and different d_1, i.e. d_1 does not affect the value of j_c. The spiking of the second region occurs, when Φ_0 becomes equal to the expression on the right-hand side of the inequality (A.8), i.e.

$$\Phi_0 = \Phi_0(2) = \frac{d_2^2}{2l_2^2} + \frac{d_1^2(l_2^2 - l_1^2)}{2l_1^2 l_2^2}. \tag{4}$$

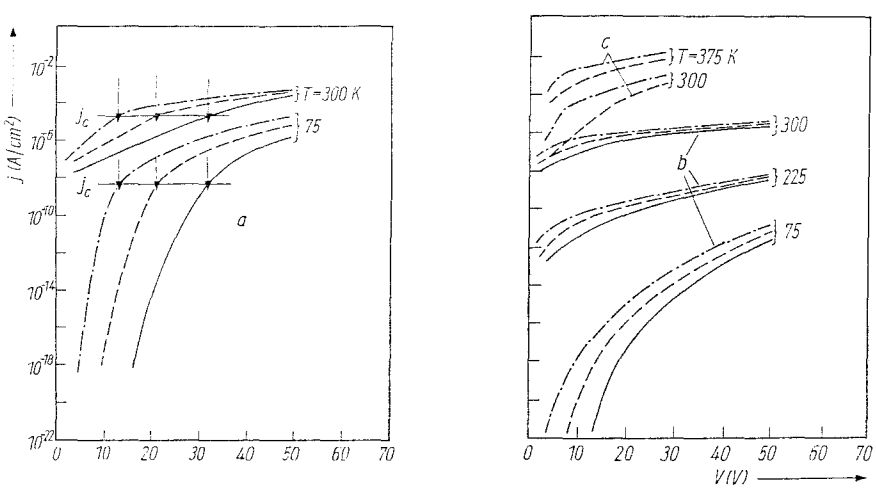

Fig. 2. The dependence of the tunnel current j on the reveres bias V for the Lo–Hi–Lo structure with $N_1 = N_3 = 2 \times 10^{15}$ cm^{-3}, $N_2 = 5 \times 10^{16}$ cm^{-3}, a) $d_2 = 0.5$ μm, b) $d_2 = 0.25$ μm and c) $N_1 = N_3 = 5 \times 10^{15}$ cm^{-3}, $N_2 = 1 \times 10^{17}$ cm^{-3}, $d_2 = 0.25$ μm for various values of d_1: — · — —0.05 μm, — — — —0.25 μm, ——— —0.5 μm

In order to determine the difference of the potentials between point $x = 0$ and any other point $x < d_1$ belonging to the first region, we combine (4) and (A.9) with the assumption $d = d_2$ and obtain

$$\Delta\Phi = \Phi_0 - \Phi(x) = x\left[\frac{\Delta d_2}{l_2^2} + \frac{d_1 - x/2}{l_1^2}\right]. \tag{5}$$

From (5) it can be seen that at

$$\Delta d_2 \gg \left(\frac{l_2}{l_1}\right)^2 d_1 \tag{6}$$

the second term in brackets is not essential and the change of the potential within the first Lo region is determined only by the parameters of the Hi region. Differentiating (A.9) with respect to x we see that if inequality (6) is fulfilled, the electric field in the first Lo region is homogeneous and does not depend on the parameters of this region. On the other hand, if $d_1 \lesssim \Delta d_2$, inequality (6) in the Lo–Hi–Lo structures is fulfilled because $(l_1/l_2)^2 = N_1/N_2 \ll 1$. Since under the condition (6) the change of the potential $\Phi(x)$ for structures with the same Δd_2 but different d_1 is identical, the tunnel currents j_c through these structures are also identical, because they are determined by the potential barrier width which depends on $\Phi(x)$ only.

From (4) it is seen that $\Phi_0(2) \sim 1/k_0T$ and the spiking voltage V_c of the Hi region does not depend on the temperature as presented in Fig. 2. Decreasing the Hi region thickness the current decrease is stronger the lower the temperature and the applied voltage.

Usually [1 to 5] from (1) one obtains the analytical expressions for $j(V)$ by expansion of the exponent of (1) in powers of $(E_x - E_m)$,

$$\alpha \int_{x_1}^{x_2} \sqrt{U(x) - E_x}\, dx = b_1 + c_1(E_m - E_x) + f_1(E_m - E_x)^2 . \tag{7}$$

The following two types of tunneling are distinguished [1 to 5]:

1. Field emission (FE), which is realized at low temperatures or high voltages, when the electrons tunneling near the Fermi level (see Fig. 1, a) contribute mainly to (1) and E_m in (7) is replaced by ζ_m.

2. Thermofield emission (TFE) which is realized at high temperatures and small bias when the current is determined mainly by the electrons with energy E_m (see Fig. 1a) which is greater than the Fermi energy but less than the barrier height. Note that E_m is determined from the condition

$$c_1(E_m)\, k_0T = 1 . \tag{8}$$

In (7) and (8) b_1, c_1, f_1 are coefficients of the Taylor expansion. Substituting $U(x)$ from Appendix into (7) one obtains $j(V)$ for FE and TFE, however, it is not convenient to use these expressions because of two reasons:

1. There is a wide range of temperatures and fields where there occurs a sufficiently smooth change from TFE to FE and the expressions valid for TFE and FE cannot be applied.

2. The dependences of D on E_x, as seen from Fig. 3, are smooth especially for the case of TFE. Because of this the formulae for FE and TFE deliver only a characteristic behaviour of the $j(V)$ dependence and essentially diminish the values of j. The accuracy of these formulae increases with decreasing temperature and growing V when $D(E)$ becomes more and more narrowed (Fig. 3).

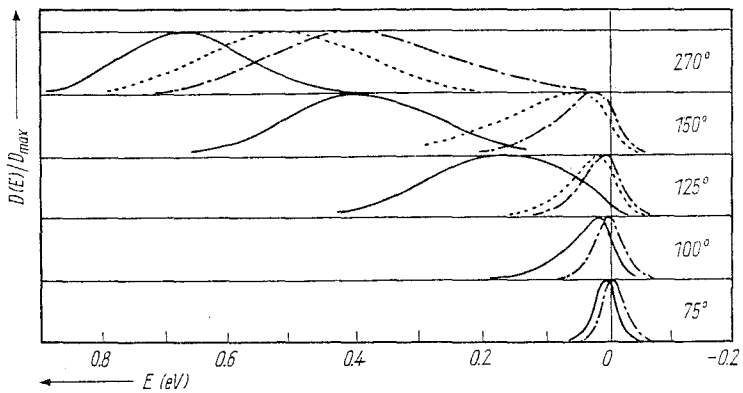

Fig. 3. The dependence of D on the energy E_x for various values of the reverse bias V in the structure with $N_1 = N_3 = 2 \times 10^{15}\,\mathrm{cm}^{-3}$, $N_2 = 5 \times 10^{16}\,\mathrm{cm}^{-3}$, $\Delta d_2 = 0.25\,\mu\mathrm{m}$, $d_1 = 0.25\,\mu\mathrm{m}$; $V = 10$ V ———, 30 V — · — ·, 50 V — — —

Nevertheless, the concepts of FE and TFE remain useful even in cases when (7) is not justified. At 300 K in all cases considered TFE is realized, at 77 K FE. Fig. 3 presents the shift of the maximum on the $D(E_x)$ dependence towards small energies with increasing V and decreasing T. At 100 and 125 K with growing V there occurs a TFE to FE transition which is also demonstrated in Fig. 3. The values of V (at which such a transition occurs) are obtained from (9) and the formulae of the Appendix if in (8) E_m is taken to be ζ_m and from the analysis of the dependences of Fig. 3 coincide. It should be stressed that at the transition from TFE to FE threre occurs a decrease of $\mathrm{d}j/\mathrm{d}V$ because in TFE the current decreases with V growing due to both barrier narrowing and decreasing E_m. In the case of FE only the first reason remains.

The above-mentioned peculiarities on I–V characteristics caused by Hi region spiking or by TFE to FE transition are common to all Lo–Hi–Lo structures. Only the voltage, at which these peculiarities are observed, differs for different structures. The I–V characteristics for a structure with high doping ($N_1 = N_3 = 5 \times 10^{16}\,\mathrm{cm}^{-3}$ and $N_2 = 10^{17}\,\mathrm{cm}^{-3}$) are illustrated in Fig. 2. There is still one more peculiarity observed for these structures — the high sensitivity of the current magnitude with respect to the barrier height. The decrease of the chosen value $eV_0 = 0.9$ eV to 0.8 and 0.7 eV leads to a great current decrease (see Fig. 4).

Experimental investigations of the field currents in Lo–Hi–Lo Schottky diodes were carried out by Konakova et al. In this paper we do not give a detailed comparison with the experimental results which will be published by Konakova later, but here we only indicate the fact of the qualitative agreement between the calculated and experimental I–V characteristics.

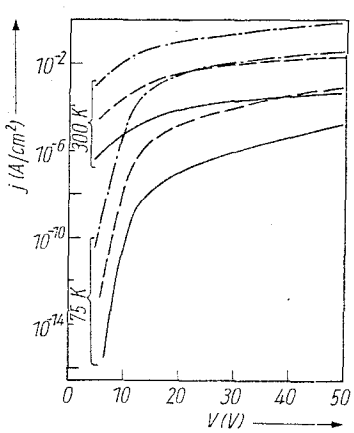

Fig. 4. The dependence of the tunnel current on the reverse bias V for the same structure as in Fig. 2a and $d_1 = 0.05\,\mu\mathrm{m}$ for various values of eV_0: — · — · 0.7 eV; — — — 0.8 eV, ——— 0.9 eV

Appendix

The dependence $\Phi(x)$ (3) for a Lo–Hi–Lo structure is determined from the Possion equation

$$\frac{d^2\Phi}{dx^2} = \frac{4\pi e^2}{\varepsilon k_0 T} N(x) . \tag{A1}$$

The boundary conditions are the value of the potential $\Phi(x)$ at $x = 0$ and a zero potential the boundary of the depletion region $x = d$,

$$\Phi_{x=d} = 0; \qquad \Phi_0 = \Phi_{x=0} = \frac{e(V + V_0)}{k_0 T} . \tag{A2}$$

The extension of the depletion region d in (A2) is not known. It is determined from the condition of a zero electric field at $x = d$,

$$\left.\frac{d\Phi}{dx}\right|_{x=d} = 0 . \tag{A3}$$

Considering that $N(x)$ is changed with x step-wise (Fig. 1 b) we obtained four different cases in dependence on the region which is spiked, i.e. on the relation between d and d_1, d_2, d_3.

1. At small voltages, when

$$\Phi_0 < \frac{d_1^2}{2l_1^2} \tag{A4}$$

and even the first Lo region is not spiked ($d < d_1$) we have the usual dependence

$$\Phi(x) = \frac{(x - d)^2}{2l_1^2} , \tag{A5}$$

where

$$d = l_1 \sqrt{2\Phi_0} \tag{A6}$$

is the extension of the depletion region, and the determination of the Debye lengths in each of the layers is

$$l_i = \sqrt{\frac{\varepsilon k_0 T}{4\pi e^2 N_i}} \tag{A7}$$

for all cases, with ε denoting the dielectric constant.

2. If only the first region is spiked,

$$\frac{d_1^2}{2l_1^2} < \Phi_0 < \frac{d_2^2}{2l_2^2} + \frac{d_1^2(l_2^2 - l_1^2)}{2l_1^2 l_2^2} , \tag{A8}$$

then in the first region $x < d_1$ we have

$$\Phi(x) = \frac{(x - d_1)^2}{2l_1^2} + \frac{(d - d_1)\,(d + d_1 - 2x)}{2l_2^2} \tag{A9}$$

and in the second region at $d_1 < x < d_2$ (A5) may be used if we replace l_1^2 for l_2^2. Here

$$d = l_2 \sqrt{2\left[\Phi_0 - \frac{d_1^2(l_2^2 - l_1^2)}{2l_1^2 l_2^2}\right]}; \qquad d_1 < d < d_2 . \tag{A10}$$

3. If the second region is spiked

$$\frac{d_2^2}{2l_2^2}+\frac{d_1^2(l_2^2-l_1^2)}{2l_1^2l_2^2}<\Phi_0<\frac{d_3^2}{2l_3^2}+\frac{d_2^2(l_3^2-l_2^2)}{2l_2^2l_3^2}+\frac{d_1^2(l_2^2-l_1^2)}{2l_1^2l_2^2}, \tag{A11}$$

then at $x < d_1$

$$\Phi(x)=\frac{(x-d_1)^2}{2l_1^2}+\frac{(d_2-d_1)\,(d_2+d_1-2x)}{2l_2^2}+\frac{(d-d_2)\,(d+d_2-2x)}{2l_3^2}, \tag{A12}$$

at $d_1 < x < d_2$ (A9) may be used, if we replace l_1 for l_2; d_1 for d_2; l_2 for l_3 and at $d_2 < < x < d$ — (A5) if we replace l_1 for l_3. Here $d_2 < d < d_3$ and

$$d=l_3\sqrt{2\left[\Phi_0-\frac{d_1^2(l_2^2-l_1^2)}{2l_1^2l_2^2}-\frac{d_2^2(l_3^2-l_2^2)}{2l_2^2l_3^2}\right]}. \tag{A13}$$

4. If Φ_0 exceeds the value of the right-hand side of inequality (A11) the whole sample is spiked ($d = d_3$) and for $x = d$ the electric field is not equal to zero as for $d < d_3$. In this case condition (A3) is replaced by $d = d_3$ and the value of the field at $x = d_3$ depends on Φ_0. For $\Phi(x)$ we have

$$\Phi(x)=\Phi_0+Cx+\frac{x^2}{2l_1^2} \qquad \text{at} \quad x<d_1, \tag{A14}$$

$$\Phi(x)=\Phi_0+Cx+\frac{(x-d_1)^2}{2l_2^2}+\frac{2d_1x-d_1^2}{2l_1^2} \qquad \text{at} \quad d_1<x<d_2, \tag{A15}$$

$$\Phi(x)=\Phi_0+Cx+\frac{(x-d_2)^2}{2l_3^2}+\frac{(d_2-d_1)\,(2x-d_1-d_2)}{2l_2^2}+\frac{d_1(2x-d_1)}{2l_1^2} \qquad \text{at} \quad d_2<x<d_3, \tag{A16}$$

where C is a value proportional to the field at $x = 0$

$$C=\frac{1}{d_3}\left\{-\Phi_0-\frac{(d_3-d_2)^2}{2l_3^2}-\frac{(d_2-d_1)\,(2d_3-d_1-d_2)}{2l_2^2}-\frac{d_1(2d_3-d_1)}{2l_1^2}\right\}.$$

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