The Journal of National Chiao Tung University
Vol. 3, September 1977
pp. 43-48

雙飄層構造抵穿能障二極體之電流——電壓特性

The Current-Voltage Characteristics of the Reach-Through BARITT Diode with Double Drift Layer Structure

余水陽 Swei-Yam Yu

Department of Electronic Engineering, N. C. T. U.

(Received June 30, 1977)

Abstract —The current-voltage characteristics of the $p^+n_1n_2p^+$ reach-through BARITT diode has been derived over the entire current range, by combining the thermionic injection effect at the injection junction and the space charge effect in the drift region. The characteristics are calculated for various doping densities N_{D1} and thicknesses x_s of the n_1 layer. At low current injection levels, the current has the thermionic emission form, that is $J \sim A^*T^2 \exp((V_{FB_2}+V_{FB_1}(2\frac{\ell}{x_2}-1)-V)^2/4V_T V_{FB})$; at higher current levels, the current has the space charge limited form, that is $J \sim V$. The d.c. conductance of both the $p^+n_1n_2p^+$ and the $p^+n_2p^+$ structures are compared, and it is found that the slope of the J-V curve for the $p^+n_2p^+$ structure is greater by the factor$(N_{D1}/N_{D2})^{1/2}$ than that for the $p^+n_1n_2p^+$ structure.

I. Introduction

A great deal of interest in the BARITT diode has been shown recently. This microwave device has a much lower noise level than IMPATT type oscillators. The current-voltage (J-V) characteristics of the BARITT diode with a p^+np^+ structure have been derived and experimentally measured[1]. The double drift $p^+n_1n_2p^+$ layer structure has been introduced due to its higher output power and higher frequency performance[2,3]. In this paper the generalized J-V characteristics of the $p^+n_1n_2p^+$ structure is derived for the entire current range (i.e. from the low thermionic injection current to the high, space charge limited current) by considering the interaction of the thermionic injection mechanism at the forward biased junction and the space charge effects in the completely depleted drift region.

In section II, the j-v characteristics are studied for various widths and doping densities of the n_1 and n_2 layers. In section III the characteristics of the p^+np^+ structure as a limiting case of the $p^+n_1n_2p^+$ structure and the dc conductance of both are compared.

II. Current-Voltage Characteristics of the $P^+n_1n_2p^+$ Structure

The model of a one-dimensional $p^+n_1n_2p^+$ structure is shown in Fig. (1a). In the following discussion, we assume an abrupt junction. The doping density in each region is of an order such that $N_A \gg N_{D1} \gg N_{D2}$, and the polarity of applied voltage is fixed so that p^+n_1 junction is always forward biased. The field profile after reach-through condition is shown in Fig. (1b). In Fig. (1b) W is the depletion width of p^+n_1 junction, x_s is the total width of n_1 layer, $\ell - x_s$ is the total width of n_2 layer.

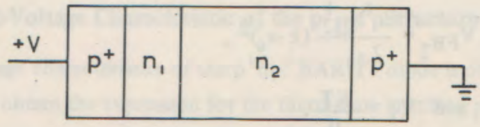

Fig. 1 (a) The one dimensional model of the $p^+n_1n_2p^+$ BARITT diode

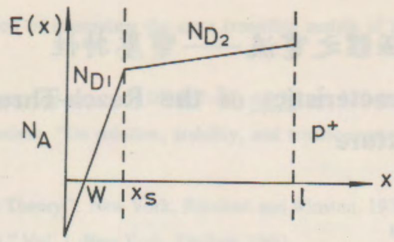

Fig. 1 (b) The electric field distribution of the BARITT diode with the dc bias at the reach-through condition.

After the reach-through condition is achieved the current is injected across the fowward biased p^+n_1 junction by the thermionic emission mechanism. The current drifts through the completely depleted n_1n_2 layer. The applied voltage is modulated by the thermionic injection current at the forward biased p^+n_1 junction and space charge effect in the n_1-n_2 depleted drift region. It is easily shown [1] that

$$J = A^*T^2 \exp\left[-\frac{q(V_{bi}-V_1)}{KT}\right] \tag{1}$$

where

$$V_{bi} - V_1 = \frac{q N_{D1}}{2\epsilon_s} W^2 \tag{2}$$

and

$$V_2 = \frac{q N_{D1}}{2\epsilon_s}(x_s - W)^2 \tag{3}$$

$$V_3 = \frac{q N_{D2}}{2\epsilon_s}\left(1+\frac{J}{J_2}\right)(\ell - x_s)^2 + \frac{q N_{D1}}{\epsilon_s}(x_s - W)(\ell - x_s) \tag{4}$$

$$J_2 = q N_{D2} v_s \tag{5}$$

$$V = V_1 + V_2 + V_3 \tag{6}$$

In Eq. (1), A* is the effective Richardson constant[1], V_{bi} is the built-in voltage of p^+n_1 junction, V_1, V_2, V_3 are the voltage drop across the p^+n_1 junction, the n_1 and the n_2 layers, respectively. The saturation drift velocity v_s is assumed to be the carrier velocity through the whole of the n_2 region.

Using Eqs. (1) through (5) and some algebraic manipulation, the expression for the total voltage drop may be obtained:

$$V = V_{FB_1}\left(2\frac{\ell}{x_s}-1\right) + V_{FB_2}\left(1+\frac{J}{J_2}\right) - 2\left(V_{FB}V_T \ln\frac{A^*T^2}{J}\right)^{1/2} \tag{7}$$

where

$$V_{FB_1} = \frac{q N_{D1}}{2\epsilon_s} x_s^2,\quad V_{FB_2} = \frac{q N_{D2}}{2\epsilon_s}(\ell - x_s)^2,$$

$$V_{FB} = \frac{q N_{D1}}{2\epsilon_s}\ell^2, \text{ and } V_T = \frac{KT}{q}.$$

At low current level, (i.e., $J << J_2$), the modulation of applied voltage is dominated by the thermionic injection mechanism,and Eq. (7) becomes

$$J \simeq A^*T^2 \exp\left[-\frac{[V_{FB_2}+V_{FB_1}(2\frac{\ell}{x_s}-1)-V]^2}{4V_T V_{FB}}\right] \tag{8}$$

At high current level (i.e., $J >> J_2$), the modulation of applied voltage is dominated by space charge effect in the n_2 layer. In this limit, Eq. (7) becomes

$$V \simeq V_{FB_1}(2\frac{\ell}{x_s}-1)+V_{FB_2}\frac{J}{J_2} \tag{9}$$

In Fig. (2) we plot J vs. V at room temperature for various values of N_{D1} and X_s. In Fig. (2), we use the numerical values $N_{D2}=5\times10^{14}$ cm^{-3}, $\ell=8.5\mu$, $A^*T^2=1.0568\times10^{11}$ Amp/m^2, $J_2=5.696\times10^6$ Amp/m^2; and (a) $N_{D1}=5\times10^{16}$cm^{-3}, $0.4\mu > x_s$ x.15μ ; and (b) $N_{D1}=1\times10^{15}$ cm^{-3}, $7\mu > x_s > 0.5\mu$.

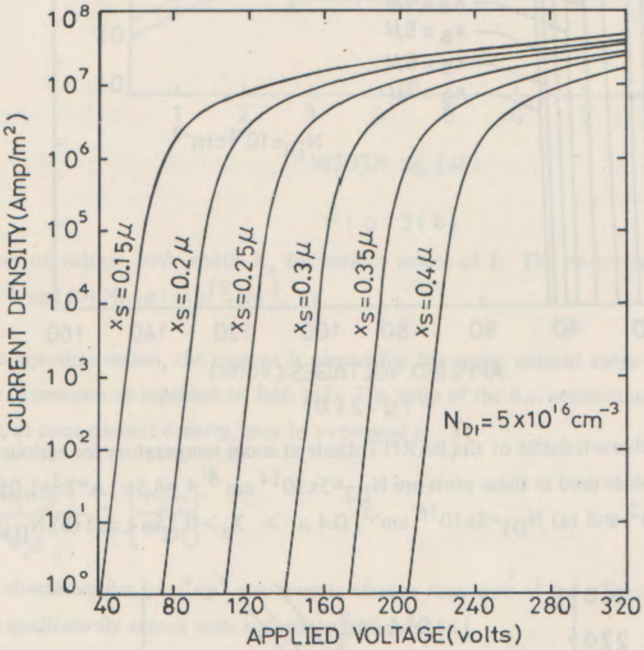

Fig.2(a)

For the various values of parameters we see that J-V characteristics have common feature: at low current levels, the current is characterized by thermonic injection as expressed in Eq. (8). As the current level increases, the influence of space charge effect increased, the slope of J-V characteristics decreases. At higher current level, the space charge effect dominated, and the current follows the expression in Eq. (9). In Fig. (3), we plot V vs. x_s for various J. In Fig. (3a) $N_{D1}=5\times10^{16}$ cm^{-3}, and in Fig. (3b) $N_{D1}=1\times10^{15}$ cm^{-3}. In the thermionic injection regime, the curves are in parallel, while at higher current level, the curves deviate from parallel and become more horizontal.

III. The Generalized Current-Voltage Characteristic of the p^+np^+ Structure

The generalized current-voltage characteristics of the p^+np^+ BARITT diode is obtained by letting $\ell = x_s$ and $N_{D1} = N_{D2}$ in Eq. (7); in this limit we obtain the expression for the thermionic injection region,

$$J = A^*T^2 \exp\left[-\frac{(V_{FB}-V)^2}{4V_T V_{FB}}\right] \tag{10}$$

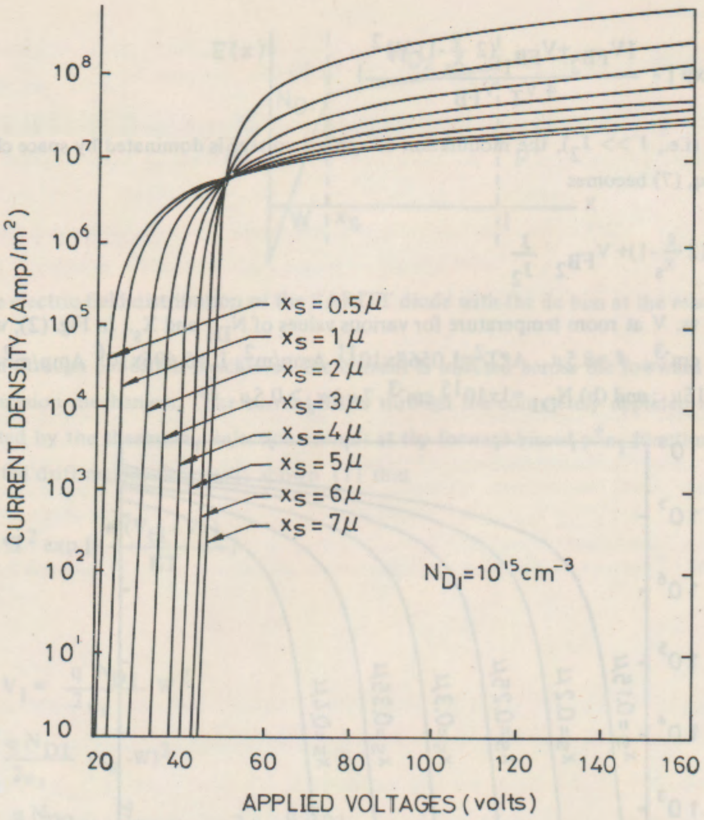

Fig. 2(b)

Fig. 2 The current-voltage characteristics of the BARITT diode at room temperature for various values of N_{D1} and X_s. The numerical values used in these plots are $N_{D2}=5\times10^{14}$ cm^{-3}, $\ell=8.5\,\mu$, $A^*T^2=1.0568\times10^{11}$ Amp/m^2, $J_2=5.69\times10^6$ Amp/m^2 and (a) $N_{D1}=5\times10^{16}$ cm^{-3}, $0.4\,\mu > X_s > 0.15\,\mu$; and (b) $N_{D1}=1\times10^{15}$ cm^{-3}, $7.0\,\mu > x_s > 0.5\,\mu$.

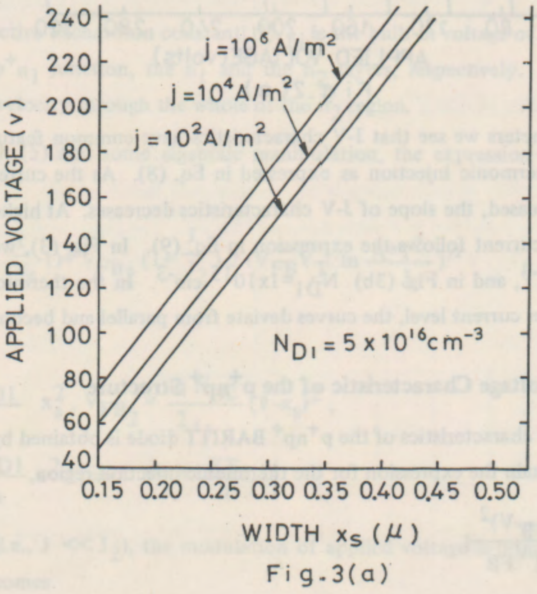

Fig. 3(a)

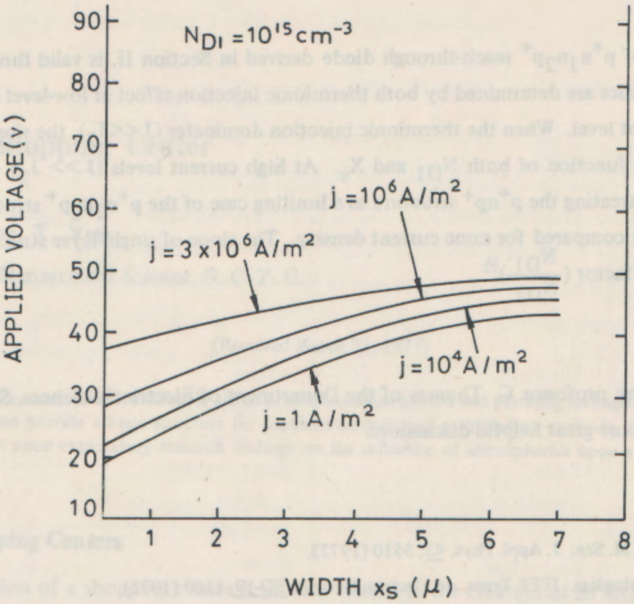

Fig. 3(b)

Fig. 3 The variation of voltage with width X_s for various values of J. The numerical values used are (a) $N_{D1} = 5 \times 10^{16}\ cm^{-3}$, and (b) $N_{D1} = 1 \times 10^{15}\ cm^{-3}$.

In the thermionic injection region, the current is ploted for the entire current range in Fig. (4), the expression in Eq. (10) is the same expression as reported in Ref. [1]. The ratio of the d.c. conductance, $\frac{dJ}{dV}$ of the p^+np and the $p^+n_1n_2p^+$ structures, at same current density, may be expressed as

$$\frac{\left.\frac{dJ}{dV}\right|_{p^+n_1n_2p^+}}{\left.\frac{dJ}{dV}\right|_{p^+n_2p^+}} = \left(\frac{N_{D2}}{N_{D1}}\right)^{1/2} \tag{11}$$

The slope of J-V characteristics in p^+np^+ structure is steeper than that of the $p^+n_1n_2p^+$ structure by the factor $\left(\frac{N_{D1}}{N_{D2}}\right)^{1/2}$, which is qualitatively agreed with experimental report [4].

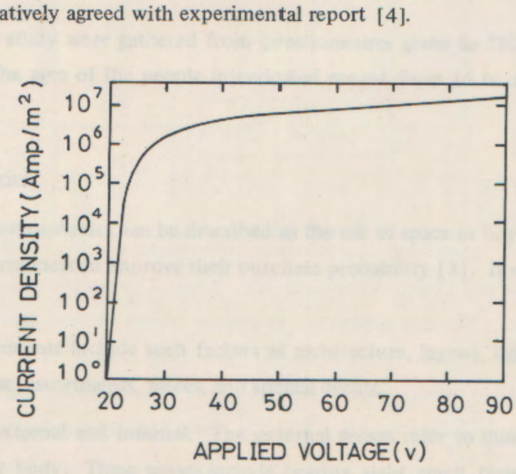

Fig. 4 The current-voltage characteristics of the p^+np^+ BARITT diode over the entire current range. The numerical values used are $N_{D1} = N_{D2} = 5 \times 10^{14}\ cm^{-3}$, $\ell = 8.5\mu$, $V_{FB} = 28.9V$, and at room temperature.

IV. Discussion

The J-V characteristic of $p^+n_1n_2p^+$ reach-through diode derived in Section II, is valid throughout the whole current range. The characteristics are determined by both thermionic injection effect at low-level injection and the space charge effect at high current level. When the thermionic injection dominates ($J \ll J_2$), the slope is only a function of N_{D1} and the intercept is a function of both N_{D1} and X_s. At high current levels ($J \gg J_2$), the space charge effect dominated and $J \sim V$. By treating the p^+np^+ structure as a limiting case of the $p^+n_1n_2p^+$ structure, the d.c. conductance of both structures are compared for same current density. The slope of single layer structure is steeper than the double layer structure by a factor $(\frac{N_{D1}}{N_{D2}})^{1/2}$.

V. Acknowledgement

The author wish to thank professor G. Thomas of the Department of Electrical Sciences, State University of New York at Stony Brook, for some great helpful discussions.

References

1. J. L. Chu, G. Persky, and S. M. Sze. J. Appl. Phys. 43, 3510 (1972).
2. Craig P. Snapp and Peter Weissglass. IEEE Trans. on Electron Devices, ED-19, 1109 (1972).
3. S. Y. Yu and G. Thomas, unpublished.
4. E. P. EerNisse, Appl. Phys. Letter 20, 301 (1972).