Pramāṇa - J. Phys., Vol. 27, No. 3, September 1986, pp. 459–468. © Printed in India.

Switching behaviour of unijunction transistor in the presence of magnetic field

S L AGRAWAL and R SWAMI*
Department of Physics, Banaras Hindu University, Varanasi 221 005, India

MS received 7 October 1985; revised 17 April 1986

Abstract. The influence of magnetic field on some switching parameters (turn-on time, turn-off time and amplitude of the current pulse appearing at base 1 terminal) of a unijunction transistor has been theoretically and experimentally investigated. The various switching parameters are shown to be governed by the magneto-concentration effect.

Keywords. Unijunction transistor; switching behaviour; magnetic field.

PACS No. 85·80

1. Introduction

Information processing systems play an important role in microelectronics. Transducers form a basic building block for these systems. This has led to the development of a variety of semiconductor transducers (Cristoloveanu 1981a; Dorey 1981; Middlehoek 1983). Recently, various silicon switching devices including unijunction transistor (UJT) have been studied extensively as magnetic sensors (Esaki and Haering 1962; Vikulin 1978; Agrawal and Swami 1981). Of these, UJT is specially promising because of its simple structure and higher magnetosensitivity (Agrawal and Swami 1981; Gasanov 1978; Karakushan *et al* 1978). Switching speed is one of the relevant parameters of UJT on which the effect of magnetic field has not yet been investigated. This speed depends upon the transit time and lifetime of minority carriers (in the emitter base 1 region of UJT) which in turn would depend upon the magnetic field. In view of the above, various electronic parameters of the device, namely, the turn-on time, the turn-off time and the amplitude of current pulse pertaining to the switching speed have been investigated in the presence of magnetic field.

2. Theoretical analysis

2.1 *Magnetic field effect on turn-on time*

Suran (1957) associated the turn-on time of UJT for large capacitances to the transit time effect and this is given by the relation

$$t_{ON} = t_t = d^2/(\mu_p V_B), \tag{1}$$

* since deceased.

where $V_B = \eta V_{BB}$, μ_p is the minority carrier mobility, d is the emitter base 1 distance in UJT bar, η is the intrinsic stand-off ratio and V_{BB} is the voltage applied between base 2 and base 1 terminal. For small capacitive loads, this expression does not hold good as the operating point of UJT cannot be considered in the saturation region upon firing (Doyle 1973).

Figure 1(a) gives a typical relaxation oscillator circuit. The equivalent circuit controlling the output waveform is given in figure 1(b). The details of the waveform for high and low capacitance values are shown in figure 1(c). In the equivalent circuit, resistance R has not been indicated since the current flowing through R is negligible as compared to the discharging current. The nodal equation for figure 1(b) is:

$$\frac{Q}{C} + I(R_1 - \bar{R}_d) + \bar{L}\frac{dI}{dt} = 0, \tag{2}$$

where Q is the instantaneous charge on the capacitor, I is the current during the discharge process, $\bar{R}_d$ and $\bar{L}$ are the effective average resistance and inductance of UJT. The solution of (2) in the form of current I is

$$I = \frac{-V_p \exp\left\{-\left(\frac{R_1 - \bar{R}_d}{2\bar{L}}\right)t\right\}}{2\bar{L}\left\{\left(\frac{R_1 - \bar{R}_d}{2\bar{L}}\right)^2 - \frac{1}{\bar{L}C}\right\}^{1/2}} \left[\exp\left\{-\left\{\left(\frac{R_1 - \bar{R}_d}{2\bar{L}}\right)^2 - \frac{1}{\bar{L}C}\right\}^{1/2} t\right\} - \exp\left\{\left\{\left(\frac{R_1 - \bar{R}_d}{2\bar{L}}\right)^2 - \frac{1}{\bar{L}C}\right\}^{1/2} t\right\}\right], \tag{3}$$

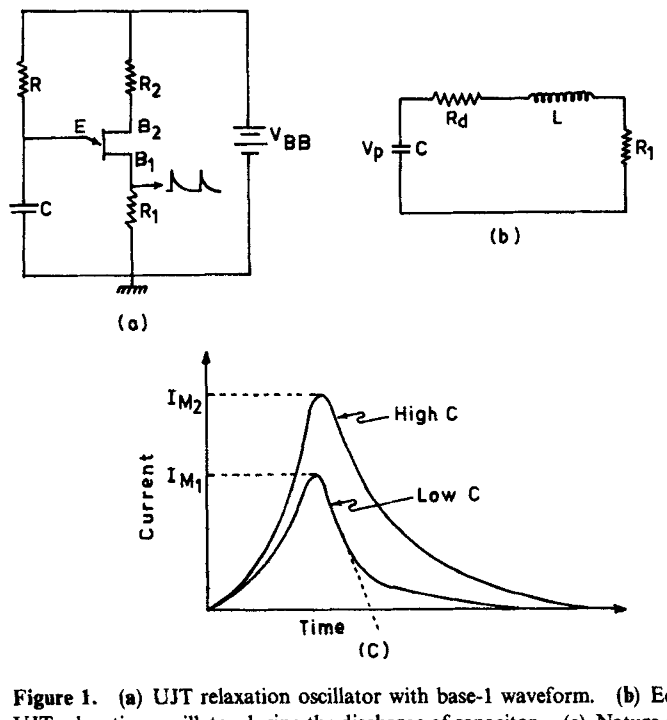

Figure 1. (a) UJT relaxation oscillator with base-1 waveform. (b) Equivalent circuit of UJT relaxation oscillator during the discharge of capacitor. (c) Nature of current pulse for low and high capacitances.

where V_p is the peak point voltage of UJT. According to this expression, the current pulse behaviour during the discharge process would be determined by the following term

$$\left\{\left(\frac{R_1 - \bar{R}_d}{2\bar{L}}\right)^2 - \frac{1}{\bar{L}C}\right\}^{1/2}$$

The circuit would show oscillatory, critically damped and overdamped behaviour depending upon whether $1/\bar{L}C$ is greater, equal to or less than $(R_1 - \bar{R}_d)^2/4\bar{L}^2$. For low capacitances, the oscillatory discharge is more probable since the condition

$$\frac{1}{\bar{L}C} > \left(\frac{R_1 - \bar{R}_d}{2\bar{L}}\right)^2$$

is satisfied. On simplification (3) takes the form

$$I = \frac{V_p \exp(\bar{R}_d t/2\bar{L})}{\bar{L}\{(1/\bar{L}C) - (\bar{R}_d/2\bar{L})^2\}^{1/2}} \sin[\{(1/\bar{L}C) - (\bar{R}_d/2\bar{L})^2\}^{1/2} t]. \tag{4}$$

In the above expression resistance R_1 has been omitted as we have adjusted $\bar{R}_d \gg R_1$ in the present experimental circuit. It is apparent from (4) that current is zero at time $t = 0$ and attains a maximum value at time t which is referred to as t_{ON} (the turn-on time). The decrease in current beyond this time is due to the sine factor. The sine-dominated discharge only occurs for approximately half a cycle due to superimposition of the decay of minority carriers on the capacitor discharge path in the neighbourhood of the valley point of the UJT I-V characteristics. In view of the above, the turn-on time of UJT is approximately one fourth of the total period of oscillation obtained from (4). Thus,

$$t_{\mathrm{ON}} \simeq \frac{T}{4} = \frac{\pi}{2}\left\{\frac{1}{\bar{L}C} - \left(\frac{\bar{R}_d}{2\bar{L}}\right)^2\right\}^{-1/2} \tag{5}$$

According to the above expression, t_{ON} is a function of differential negative resistance and inductance. These ($\bar{R}_d$ and $\bar{L}$) are magnetic field dependent quantities (Agrawal 1982) and hence on differentiating (5) w.r.t. magnetic field and further simplification, we get

$$\frac{1}{t_{\mathrm{ON}}}\frac{\Delta t_{\mathrm{ON}}}{\Delta B} = \frac{2t_{\mathrm{ON}}^2}{\pi^2}\left[\left\{\frac{1}{\bar{L}C} - \left(\frac{\bar{R}_d}{2\bar{L}}\right)^2\right\}\frac{1}{\bar{L}}\frac{\Delta \bar{L}}{\Delta B} + \frac{\bar{R}_d}{2\bar{L}^2}\frac{\Delta R_d}{\Delta B}\right]. \tag{6}$$

Similarly, for large values of capacitances, the change in t_{ON} as a function of magnetic field can be written from (1) as:

$$\frac{1}{t_{\mathrm{ON}}}\frac{\Delta t_{\mathrm{ON}}}{\Delta B} = -\frac{1}{\mu_p}\frac{\Delta \mu_p}{\Delta B}. \tag{7}$$

2.2 *Magnetic change in turn-off time*

According to Daw and Mitra (1970) the turn-off time of unijunction transistor for large C values is given as,

$$t_{\mathrm{off}} \simeq (R_s + R_1)\, C \ln (V_p/V_{E\min}), \tag{8}$$

where R_s is the saturation resistance of UJT, V_p is the peak point voltage and $V_{E\,min}$ is the minimum emitter voltage on static I-V characteristics curve of UJT. The magnetic field influence on the turn-off time can therefore be understood from the following equation which has been obtained upon differentiation and simplification of the above expression

$$\frac{1}{t_{\rm off}}\frac{\Delta t_{\rm off}}{\Delta B}=\frac{1}{(R_s+R_1)}\frac{\Delta R_s}{\Delta B}+\frac{1}{\ln(V_p/V_{E\min})}\left\{\frac{1}{V_p}\frac{\Delta V_p}{\Delta B}-\frac{1}{V_{E\min}}\frac{\Delta V_{E\min}}{\Delta B}\right\}. \tag{9}$$

It should be emphasized here that (8) is not valid for small value of capacitances on account of the oscillatory discharge. For such capacitance, the turn-off time comprises of a time approximately equivalent to the turn-on time (equation (5)) and a major portion of the exponential decay time of minority carriers. Therefore, the magnetically-induced change in the turn-off time for low capacitances can be readily explained in terms of the magnetic field influence on these factors. In addition, the magnetic change in the amplitude of current pulse will also be involved here since the turn-off time is considered from the initiation of turn-off to 10% of the total pulse height.

3. Experimental

Relaxation oscillator circuit of figure 1(a) has been used to measure the switching speed of a cubic-structured UJT. In this circuit, R_1 was kept quite small (5 ohm) to minimize its influence on the various switching parameters. The current pulse waveform was photographed for different magnetic fields both for low (1 nf) and high (500 nf)

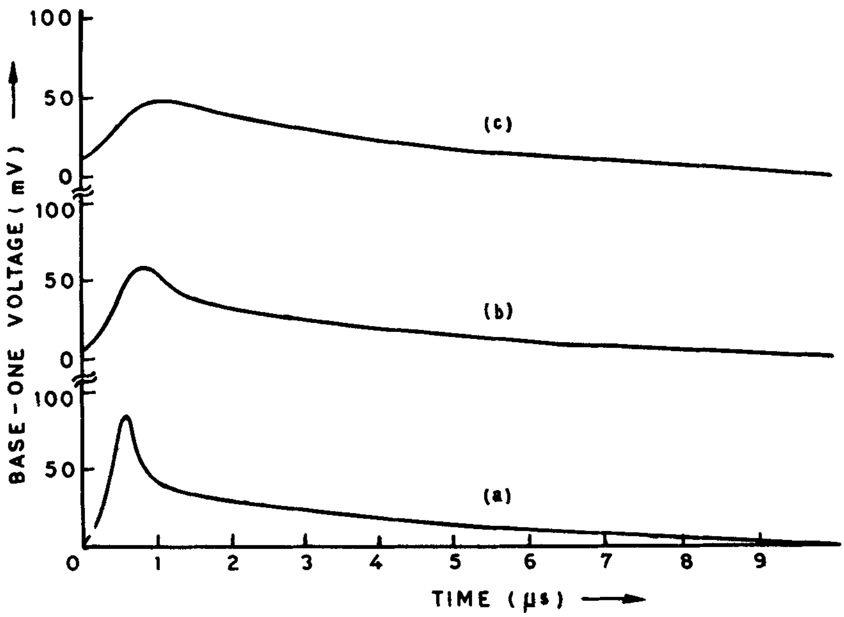

Figure 2. Voltage pulse waveform at base one of UJT for $C = 1{\cdot}0$ nf. (a) $B = 0{\cdot}0$T; (b) $B = 0{\cdot}5\,T$ and (c) $B = 1{\cdot}0$ T.

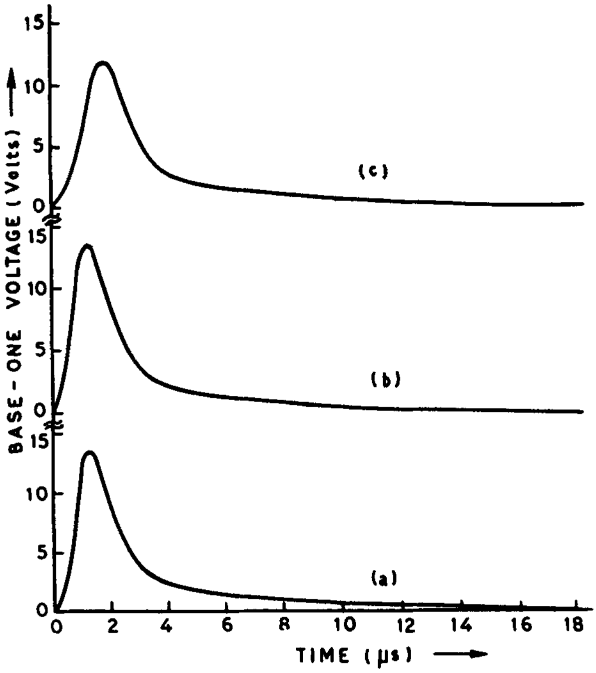

Figure 3. Voltage pulse waveform at base one of UJT for $C = 50{\cdot}0$ nf. (**a**) $B = 0{\cdot}0$ T; (**b**) $0{\cdot}5$ T and (**c**) $B = 1{\cdot}0$ T.

capacitances. Figures 2 and 3 show the current pulses obtained for three different magnetic fields. The turn-on time, the turn-off time and the amplitude of current pulse were determined from the recorded photographs. The results obtained are shown in figures 4, 5 and 6. In all the measurements the direction of magnetic field B^+ with respect to the device configuration is shown in figure 7. Moreover the magnetic field acts uniformly on the whole device (figure 7).

4. Results and discussion

4.1 *Effect of magnetic field on the amplitude of current pulse*

Magnetically-induced changes in the amplitude of current pulse (see figures 2 to 4) can be explained with the help of magnetic field-dependent differential negative resistance and inductance (Agrawal 1982; Agrawal and Swami 1985). For small capacitances, when the condition $1/\bar{L}C \gg (\bar{R}_d/2\bar{L})^2$ in (4) holds good, the amplitude is proportional to $L^{-1/2}$. Agrawal (1982) showed that L increases with the magnetic field (B^-) due to a decrease in the carrier mobilities and lifetime of the minority carriers. This decrease is on account of the deflection of carriers towards the surface of high recombination (Dobrovolski 1961; Dobrovolski and Lyashenko 1962; Cristoloveanu 1981b). The increase of L causes a decrease in the amplitude as is observed from figure 4. In the B^+ direction, the amplitude of the current pulse first increases slightly before decreasing (figure 4). This effect is more pronounced for low capacitances and is probably due to the enhancement of lifetime (carriers being deflected towards the surface of lower

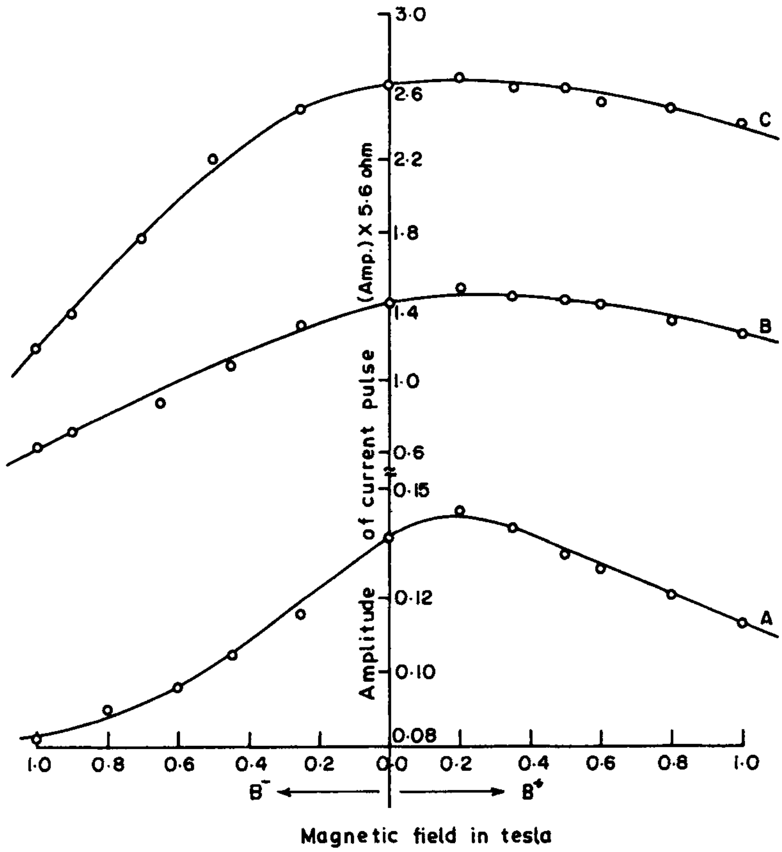

Figure 4. Variation of the amplitude of current pulse I_m with magnetic field for three capacitors. A, 1·0 nf; B, 50·0 nf; C, 500·0 nf.

recombination rate) for low values of B^+. This increase in lifetime is over-compensated for large B^+ values due to the effect of transverse diffusion current (Cristoloveanu 1981b) thus reducing the lifetime of minority carriers. Subsequently I_m decreases with high B^+ values since L increases in this case.

For large values of capacitances, the amplitude I_m is governed by the static I-V characteristics at high injection levels. When the current in the diode-dominated region of UJT decreases on account of enhanced recombination (Agrawal and Swami 1981) the amplitude I_m diminishes as the magnetic field B^- enhances. This is seen from the experimental results of figure 4. The behaviour of lifetime of minority carriers for B^+ magnetic field causes initially an increase of current in diode-dominated region of UJT before decreasing (Agrawal and Swami 1981). This in turn results in slight increase of I_m before the decreasing trend.

4.2 *Effect of magnetic field on turn-on time*

The effect of magnetic field on t_{ON} for high C values can be analyzed with the help of (7). Since the minority carrier mobility decreases with magnetic field B^-, the term $\Delta\mu_p/\Delta B$ in (7) would be negative. This causes an increase in t_{ON} with the magnetic field (B^-) for large C values as observed experimentally (figure 5). Further we note that for B^+

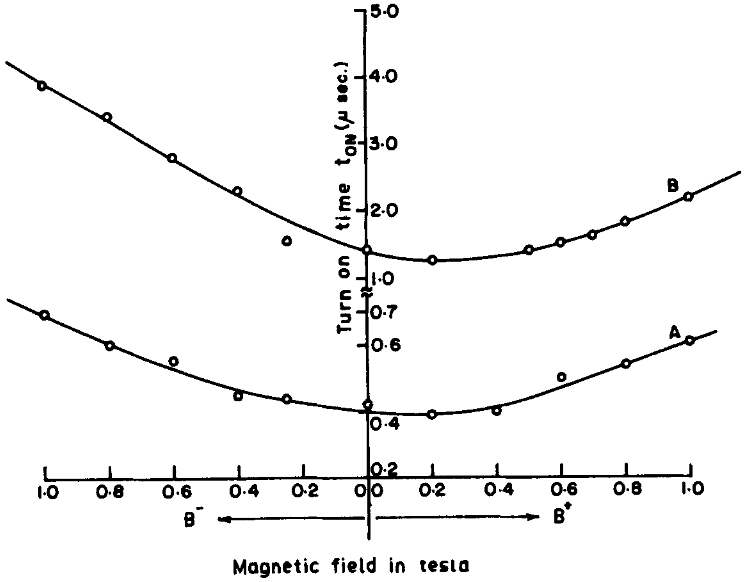

Figure 5. Variation of turn-on time of UJT with magnetic field for two capacitors. A, 1·0 nf; B, 500·0 nf.

direction t_{ON} decreases before enhancing which can be explained considering the role of carrier recombination on the mobility of holes when they are deflected towards the surface having smaller recombination velocity as discussed in §4.1.

For low C values, the magnetic field dependence of t_{ON} can be understood from (6) derived in §2.1. The two terms appearing in (6), namely, R_d and L increase in the magnetic field B^- on account of a decrease in the lifetime of minority carriers and mobilities of both types of carriers (Agrawal 1982; Agrawal and Swami 1985). Thus the terms $\Delta L/L\Delta B$ and $\Delta R_d/R_d\,\Delta B$ in relation (6) are positive which in turn enhances t_{ON} as shown in figure 5. Where we also notice that t_{ON} decreases initially with B^+ magnetic field before enhancing. This can be understood from the studies of Agrawal (1982) who found that the change in negative resistance and inductance at high injection levels depend upon the magnetic field direction causing these changes. When the carriers are deflected by magnetic field towards the surface of lower recombination velocity, the negative resistance and inductance decrease due to augmentation of the carrier mobilities and minority carrier lifetime. After a certain magnetic field, carrier mobilities and lifetime of minority carriers start decreasing due to the appearance of transverse diffusion current effects (Cristoloveanu 1981b) which increase R_d and L with magnetic field. This behaviour is obviously reflected in the dependence of t_{ON} on magnetic field in view of relation (6).

4.3 *Effect of magnetic field on turn-off time*

It is evident from (8) and (9) that the magnetically-induced change in t_{off} for large capacitances is due to the change in the static behaviour of UJT with magnetic field. The measured values of saturation resistance R_s, peak point voltage V_p and emitter voltage $V_{E\,min}$ (corresponding to 10% of the amplitude of current pulse) for different magnetic fields are given in table 1. The applicability of (8) which forms the basis of (9) explaining

Table 1. Comparison between theoretical and experimental turn-off time of UJT for $C = 500$ nf and $R_1 = 5{\cdot}6$ ohm in figure 1.

	Magnetic field B		
	0.0T	−1·0T	+1·0T
Peak point voltage V (in volts)	11·75	12·50	11·50
Amplitude of current pulse I_m (in mA)	500	200	400
Emitter voltage $V_{E\,\min}$ corresponding to 10% of I_m (in volts)	3·20	2·35	2·40
Experimental turn-off time (μsec)	19	45	22
Theoretical turn-off time (from equation (8)) (in μsec)	17·60	43·40	23·20

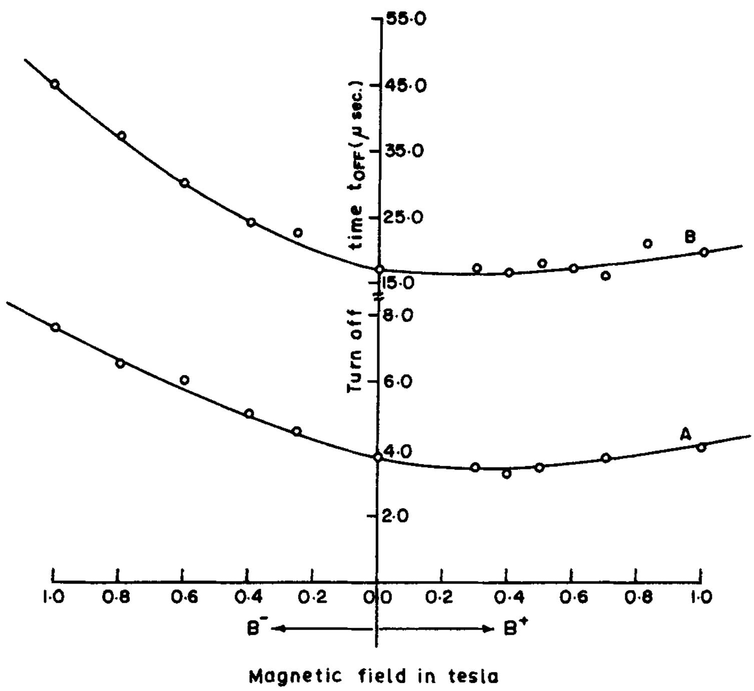

Figure 6. Variation of turn-off time of UJT with magnetic field for two capacitors. A, 1·0 nf; B, 500·0 nf.

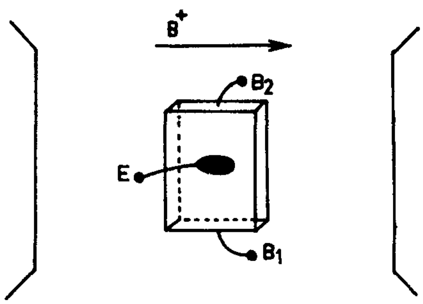

Figure 7. Direction of magnetic field with respect to device geometry.

our results has been checked by theoretically calculating t_{off} from the measured parameters given in table 1. It is obvious that the theoretical turn-off time is approximately the same as the experimental turn-off time.

The variation of turn-off time with magnetic field is shown in figure 6 for different C values. From the investigations of the magnetically-induced changes in static parameters of UJT (Agrawal and Swami 1981) it is evident that when the carriers are deflected by magnetic field towards the surface of high recombination, saturation resistance R_s increases due to decrease in the minority carrier lifetime. Also the peak point voltage V_p increases due to the well-known Hall effect and the emitter voltage $V_{E\,\text{min}}$ corresponding to 10% of I_m diminishes due to decrease of I_m for B^- magnetic field (figure 4). Therefore in view of the above and relation (9) t_{off} increases in B^- magnetic field. Again when the injected carriers are deflected towards the surface of low recombination, the saturation resistance initially decreases (due to rise in the minority carrier lifetime) and then increases when the transverse diffusion current sets in. Also the peak point voltage decreases in B^+ magnetic field (Agrawal and Swami 1981) and $V_{E\,\text{min}}$ initially increases due to enhancement of I_m (figure 4) and then diminishes due to decrease of I_m (figure 4). Therefore, for low B^+ magnetic fields (before the appearance of transverse diffusion current) t_{off} reduces and at higher B^+ values (after the appearance of transverse diffusion current) t_{off} increases.

5. Conclusion

Switching behaviour of UJT in the presence of magnetic field has been analyzed theoretically and verified experimentally on a commercially available UJT 2N2646. The results show that the various switching parameters of UJT are mainly influenced by the magneto-concentration effect and their impact on various electrophysical parameters of the device.

References

Agrawal S L 1982 *Magnetic field effects in silicon unijunction transistors and their applications*, Ph.D. thesis, Banaras Hindu University

Agrawal S L and Swami R 1981 *J. Phys.* **D14** 283

Agrawal S L and Swami R 1985 *Proc. IV National Seminar on physics of semiconductors and devices. Jaipur* (Meerut: Puneet Press) p. 194

Cristoloveanu S 1981a *International Workshop on the physics of semiconductor devices*, Abstract-poster papers (New Delhi: Allied Publishers) p. 179

Cristoloveanu S 1981b *Phys. Status Solidi* **A65** 281
Daw A N and Mitra R N 1970 *Int. J. Electron* **28** 597
Dobrovolskii V N 1961 *Sov. Phys. Solid State* **3** 1143
Dobrovolskii V N and Lyashenko V I 1962 *Sov. Phys. Solid State* **3** 1928
Dorey A P 1981 *J. Phys. Technol.* **12** 24
Doyle J M 1973 *Pulse fundamentals* (New Delhi: Prentice Hall) 2nd ed., p. 366
Esaki L and Haering R R 1962 *J. Appl. Phys.* **33** 2106
Gasanov L S 1978 *Sov. Phys. Semicond.* (*English transl.*) **12** 587
Karakushan E I, Mankulov A R, Samsonov E S and Stafeev V I 1978 *Sov. Phys. Semicond.* (*English transl.*) **12** 35
Middlehoek S 1983 *Solid state devices* (eds) A Goetzberger and M Zerbst (Weinheim: Physik Verlag) p. 73
Suran J J 1957 IEEE *Trans. Electron. Devices* **ED-4** 34
Vikulin I M 1978 *Sov. Phys. Semicond.* (*English transl.*) **12** 950