Pergamon

Solid-State Electronics Vol. 41, No. 9, pp. 1251–1255, 1997
© 1997 Elsevier Science Ltd. All rights reserved
Printed in Great Britain

PII: S0038-1101(97)00078-6

0038-1101/97 $17.00 + 0.00

PULSED OPTICAL SWITCHING OF JUNCTION PHOTOTRANSISTORS

M. J. LAZARUS and R. W. PRICE

School of Physics and Chemistry, University of Lancaster, Lancaster LA1 4YB, U.K.

(Received 6 December 1996; in revised form 21 February 1997)

Abstract This paper presents techniques for approaching the ideal theoretical waveform for switching phototransistors. Switch times of 150–250 ns have been achieved, in contrast with usual times of several microseconds. The ultimate possibilities are discussed. © 1997 Elsevier Science Ltd.

NOTATION

t_d	delay turn on time
T_R	turn on rise time
T_F	turn off fall time
t_{sd}	saturation turn off delay time
τ_F	base transit time
τ_B	mean carrier life time
Q_B	base charge
I_B	base current
V_{CC}	supply voltage
R_L	load resistance
h_{fe}	common emitter current gain ($=\beta$)
$I_{B(on)}$	base charging current
$I_{B(hold)}$	base holding current
$I_{B(off)}$	base discharging current
I_{BS}	base saturation current ($\sim I_{CS}/h_{fe}$)
I_{CS}	collector saturation current ($\sim V_{CC}/R_L$)
V_{CE}	collector–emitter voltage
I_{CE}	collector–emitter current
D	diffusion constant
W	base width

1. INTRODUCTION

The use of phototransistors has previously been limited by their poor response to high frequencies and high speed switching due to the increased carrier transition times through the larger base region. This large volume is essential to ensure a good response to illumination. To decrease switch off times, it has long been routine to use lifetime killers to remove the carriers and hence assist turn off. This, however, creates a corresponding increase in the switch on time and reduces the gain.

The present paper discusses a technique that does not produce a negative effect with the switch on. Indeed the switch on time approaches the theoretical limit without the transistor being driven into oversaturation, whilst the speed of switch off is also increased. It also comments on the benefits associated with the optical isolation of the base drive circuitry.

The precursor of this work[1] involved the driving of negative pulses of current into the base region to switch the transistor off from a non-saturated *on* state. This non-saturated *on* state was achieved by using a low level 'hold' signal once the transistor had switched on. To maximise switch on time the transistor was switched on by a large saturating pulse which was quickly reduced to the hold level once the transistor had switched on.

Obviously this technique required some modification when dealing with light since there is no optical counterpart to the negative voltage pulse[2]. The modification made use of a photodiode connected to the base lead of the phototransistor. The photodiode was then illuminated with a pulse of light during the turn off condition which had the effect of removing the excess carriers in the base region and thus reducing the switch off time.

In the preliminary work a simple differentiation circuit gave an approximation to the desired profile for the signal drive. This report will describe circuitry which allows the input signal profile to approach more closely the ideal waveforms.

The phototransistor used in these studies allowed a direct electrical connection to the base region, this is obviously necessary for this technique. The manufacturers suggested use for the base lead is to connect it to a small positive bias. However, although this additional positive current bias has the effect of reducing the time delay of switch on, it also counteracts the performance of turn off.

High speed response can be obtained with heterojunction and quantum well phototransistor structures. However, emitter–base heterojunctions invariably yield high on-state voltages for the common emitter characteristics—thus increasing the self heating and preventing high efficiency switching[3,4].

Due to the complete isolation of the input circuitry, Miller feedback effects such as ringing are completely eliminated. Moreover, the effective removal of the amplified capacitance across the collector–base junction reduces the switch on time.

The following sections report on studies of the behaviour of the phototransistor in two separate modes of operation: as a normal junction transistor controlled by base current and as a phototransistor controlled by light. This is done to highlight the possible application to a non-specifically manufactured power transistor suitably modified to allow light into the base. This behaviour is then related to the pulsed operation of the phototransistor with the base discharging photodiode.

2. THE TRANSISTOR

The phototransistor used was the Silicon Zetex BPX25. It was first studied in a common emitter arrangement in zero light with the base signal being fed directly into the base lead. This enabled the production of the characteristic collector current against voltage curves for the phototransistor being operated as a normal transistor with various constant base biases. These curves are shown in Fig. 1.

3. THE PHOTOTRANSISTOR

The phototransistor was illuminated by the high brightness Hewlett Packard HLMP8103 AlGaAs LEDs. This was previously calibrated for light output versus current.

An empirical fit to the data is

$$E = 320\left(1 - \exp\left(\frac{-I_{\text{LED}}}{30n}\right)\right) \qquad (1)$$

where E is the illuminance of the LED in Lux, I_{LED} is the current flowing through the LED in milliamps and n is a fitting factor for the individual LED which can typically range from 1 to 1.5. The multiplying factor of 320 is a function of the distance of the LED from the phototransistor which, in this case, is less than 1 mm measured from tip to tip.

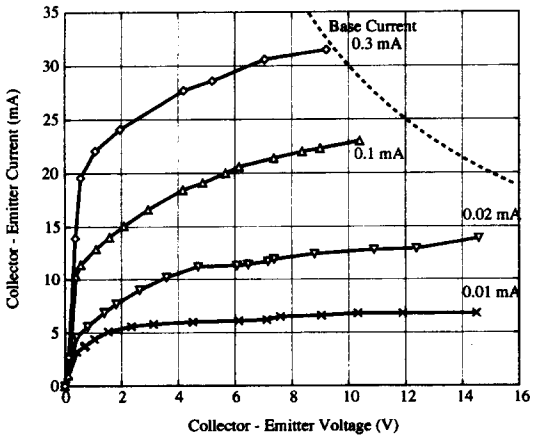


Fig. 1. Collector–emitter current versus collector–emitter voltage for the BPX25 phototransistor operated in zero light.

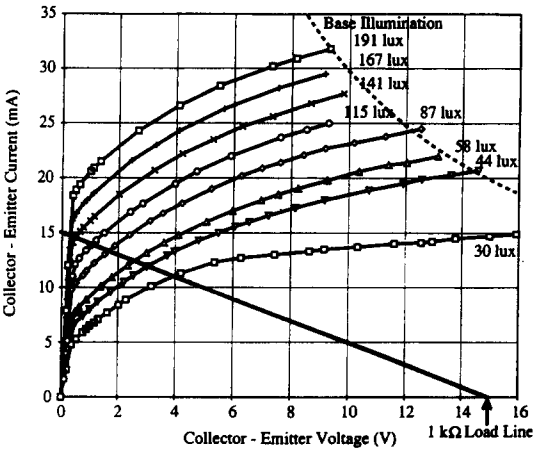


Fig. 2. Collector–emitter current versus collector–emitter voltage for the BPX25 phototransistor operated by illumination of the base.

This then allowed the measurement of the characteristic collector–emitter current against voltage for various levels of illumination of the base. These are shown in Fig. 2.

To draw an analogy between base current and switching with light, it was decided to find the base current which caused the transistor to behave in a similar fashion to that of the illumination. This can be observed initially by comparison of Figs 1 and 2. It is noted that these curves are of differing shape and 'smoothness', the curve produced by illumination is thought to be smoother due to the absence of noise introduced by the base circuitry.

The method employed to gain a more accurate understanding of the equivalent base current for illumination was to measure the response of the collector current to both base current and illumination. The results are shown in Fig. 3; the transistor was operated in a common emitter arrangement with the supply voltage, V_{CC}, set at 15 V and a load resistance, R_{L}, of 1000 Ω. There are three distinct regions of operation for the BPX25 phototransistor with differing base biases. Figure 3 shows the initial two regions but the third is not shown and is the saturated region.

The response to light can be directly correlated to a base current. An approximate empirical relation was found to be

$$I_{\text{BASE}} = \frac{E}{\gamma} + \frac{E^3}{\delta} \qquad (2)$$

where $\gamma = 1700$, $\delta = 40 \times 10^6$, I_{BASE} is the equivalent base current in milliamps and E is the illuminance of the LED in Lux.

4. PROFILED PULSE OPERATION

The profiled signal consists of three distinct sections; the first section is the large initial saturating pulse to switch the transistor on, the second is a low

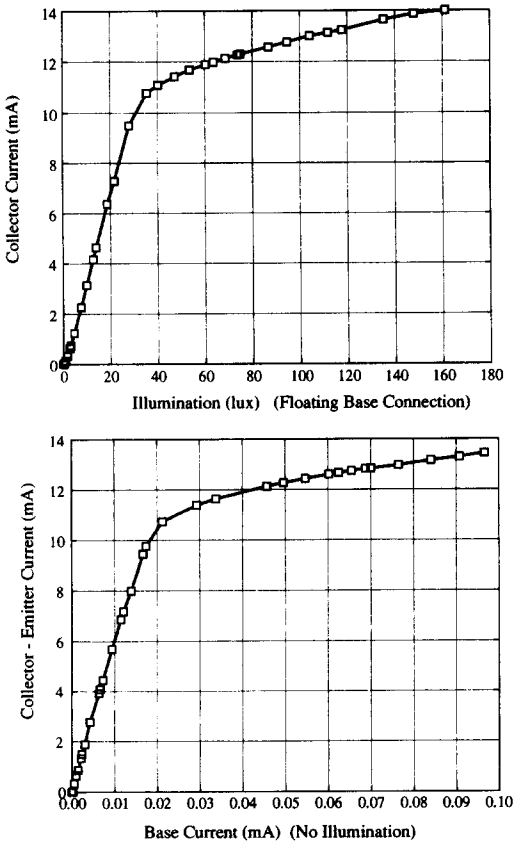


Fig. 3. Collector–emitter current versus illumination and base current for the BPX25 phototransistor.

level hold signal to just hold the transistor on and the final third stage is the turn off pulse. The turn off pulse differs from the negative current pulse used in previous studies[1,5,6] since the switching is controlled by light emitting diodes. The profile of the pulse introduced to the phototransistor base and then the photodiode is illustrated in Fig. 4.

The turn off pulse actually consists of two separate simultaneous processes; the light introduced to the phototransistor base is rapidly reduced whilst the light to the base discharging photodiode is pulsed on. The control of these light pulses is explained in detail in Section 5. Figure 5 shows schematically the technique of operation. The solid line of Fig. 4 would

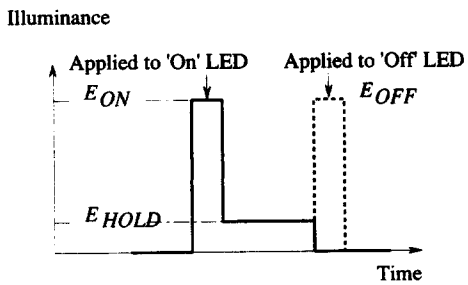


Fig. 4. Profiled light pulse; dotted line illustrates the position in time of the discharge pulse.

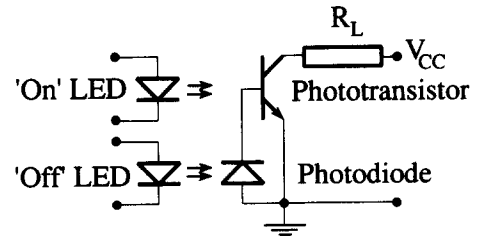


Fig. 5. Schematic diagram of the apparatus.

be produced by the 'on' LED and the dotted line by the 'off' LED.

5. EXPERIMENTAL

The driving circuit for the LEDs, see Fig. 6, is a simple wave shaping circuit consisting of five op-amps. The shaped waveform is derived from a rectangular wave. This rectangular wave is differentiated to give the peaks used for turn on and turn off. For the turn on these are added to the rectangular wave to give a hold signal, the level of which can be adjusted by varying the gain of the op-amp which takes the undifferentiated rectangular wave. It is noted that at each op-amp the signal is inverted, the 'on' signal is passed through two inverting stages and hence it is in phase with the input waveform. The positive going edge of the rectangular wave produces the turn on spike. Each LED was driven by an emitter follower arrangement which was biased by a 100 kΩ potentiometer.

The two leads to the LEDs were passed through the same current probe but in opposite directions. This enabled us to view the two LED currents on a single trace on the oscilloscope. The wires were arranged so the current through the 'off' LED gave a negative signal. The operational amplifiers used were the Elantec EL2044CN. Although the circuit did not produce the ideal rectangular pulses they could be approximated to perfect rectangular pulses of identical area.

6. TURN ON AND TURN OFF

Most theory derived for the turn on and off assumes a gain mechanism exists throughout the switching[7,8]. All of the associated balancing charge needed to retain a neutral plasma in the base has to be supplied by the majority carrier base current. We shall assume we are dealing with an *npn* transistor, as in the actual experiments. The DC gain of the transistor is produced since a small base majority current is needed to replace recombined holes when the transistor has switched on. As the recombined holes are replaced the emitter forward bias will be maintained, and minority of electrons will be injected to replace those lost due to recombination. In this steady state, the gain of the transistor is given by τ_B/τ_F.

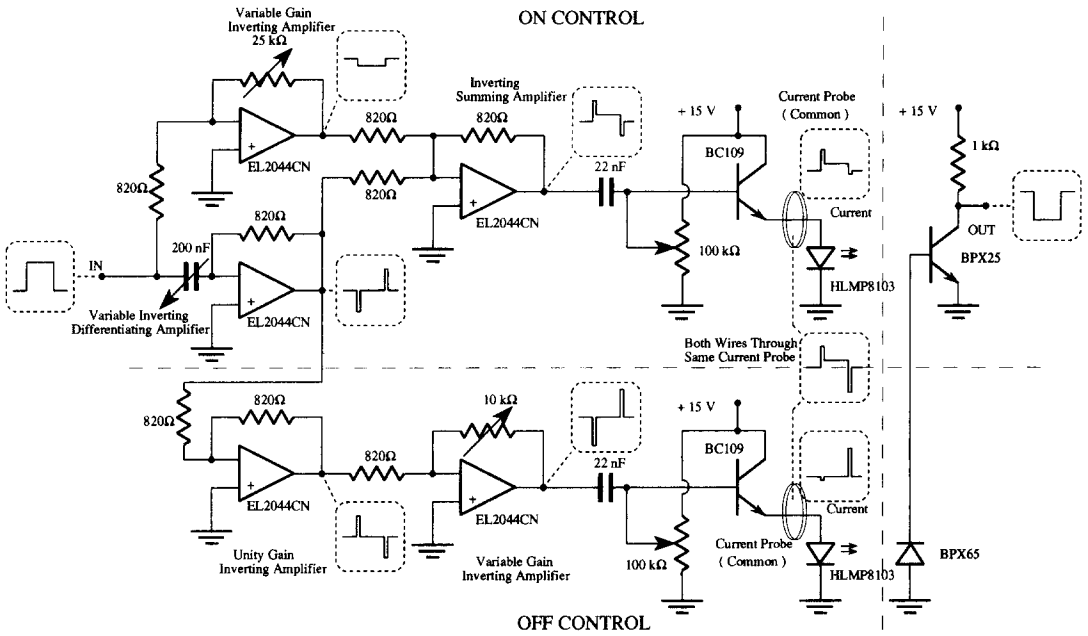


Fig. 6. Waveshaping circuit.

The profiled pulsed operation of the transistor allows one to understand the true operation of the switching transistor. If there is no loss due to recombination the transistor will merely require a switch on current pulse *and* a switch off current pulse. A hold current is only required when there is carrier loss.

The standard text book treatment[9,10] of what would be a purely diffusion transistor (i.e. diffusion current in the base with no drift field) assumes a transit time, $W^2/2D$, which depends on the diffusion only. In reality we must consider that the application of the base current and voltage of the initial turn on creates a drift field in the base which exists until electrons have been injected to give a neutral base. Therefore even without a doping gradient, there must be a drift field in the early stages of the turn on and also the turn off when the balancing hole charge is removed. Therefore, the electrons move faster than the diffusion transit time, just as would be the case with a true doping gradient[11].

For turn on, we can summarise the charging in the following equation:

$$\tau_F \frac{dI_C}{dt} = I_{B(on)} - \frac{Q_B}{\tau_B} \tag{3}$$

where $I_C = Q_B/\tau_F$. From eqn (3) we can calculate the maximum rate of change of collector current and the holding current required, once the transistor has switched on.

These considerations allow us to predict the ability to switch the transistor with light in a time faster than the steady state base transit time. The ultimate limits of the switch times are discussed in Appendix A.

7. EXPERIMENTAL RESULTS

The pulse operation of the phototransistor enabled switching off in a time less than 0.25 μs, and switching on in a time of 0.15 μs. These represent vast improvements over other commercial opto-isolators where switch times of 15 μs are not uncommon and at best are usually much larger than 1 μs. It is also noted that for the faster opto-isolators, the maximum power limitations are far inferior to that of the BPX25 phototransistor.

The switching of a 1 kΩ load is shown in Fig. 7. The upper trace is that of the current through both LEDs, the positive section corresponds to the 'on' LED operating, and the negative pulse is the current

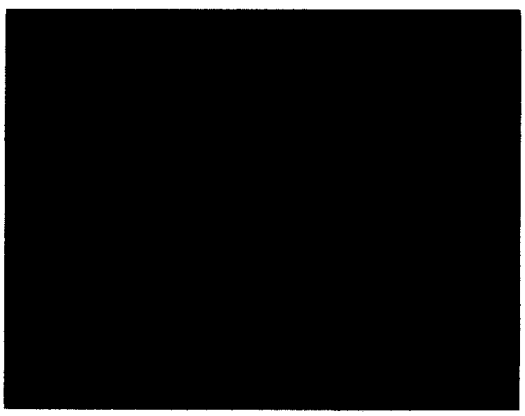


Fig. 7. Switching of the phototransistor with profiled optical drive. Upper trace: current probe waveform for LED drivers; lower trace: phototransistor collector voltage. (Positive pulse and hold current: LED 1 active; negative pulse: LED 2 active; calibration: 2 mA/mV.)

through the 'off' LED. The calibration of the current probe used was 2 mA/mV.

These operations were achieved using the red HLMP8103 LEDs. The total optical output of each was found to be 15 mW for a constant current level of 40 mA. This could be increased to approximately 25 mW for the highest pulsed currents.

8. CONCLUSION

We can now calculate, using eqn (2) and those in Appendix A, values for the illuminance of the LEDs required to turn the phototransistor hard on, E_{ON}, and to hold the transistor on, E_{HOLD}. The parameter E_{OFF} is the illuminance of the LED required to switch the discharging photodiode *on* in order to switch the phototransistor *off*. Using eqn (1) it is possible to relate these illuminances to the current required through the LED.

The possibility of switching in less than the steady state base transit time, $W^2/2D$, could be tested in the near future with the advent of powerful diode lasers. Moreover the increasing mass production of diode lasers (with faster modulation capabilities) will make viable high speed switching of optically isolated high voltage transistors.

REFERENCES

1. Lazarus, M. J. and Wilkes, J., *IEEE Trans. Circuits and Systems*, 1994, **41**, 662.
2. Lazarus, M. J., *Electron. Lett.*, 1996, **32**, 395.
3. Zhu, Y., Komatzu, Y., Noda, S., Takeda, Y. and Sasaki, A., *IEEE Trans. Electron Devices*, 1991, **ED38**, 1310.
4. Goswani, S., Bhattacharya, P. and Cowles, J., *IEEE Trans. Electron Devices*, 1993, **ED40**, 1970.
5. Lazarus, M. J., *Electron. Lett.*, 1993, **29**, 943.
6. Lazarus, M. J., *Solid-St. Electron.*, 1995, **38**, 351.
7. Le Croisette, D., *Transistors*. Prentice Hall, Englewood Cliffs, New York, 1963.
8. Tyagi, M. S., *Introduction to Semiconductor Materials and Devices*. Wiley, 1991, pp. 435–440.
9. Grove, A. S., *Physics and Technology of Semiconductor Devices*. Wiley, New York, 1967.
10. Gray and Mayer, *Analysis and Design of Analogue Integrated Circuits*. Wiley, New York, 1993.
11. Roy, B. C. and Chakrabarti, N. B., *IEEE Trans. Electron Devices*, 1987, **ED34**, 1482.

APPENDIX A: ULTIMATE SWITCH TIMES

We can use eqn (3) to give:

$$\tau_F \frac{dI_C}{dt} = I_{B(on)} - I_C \frac{\tau_F}{\tau_B}. \tag{A1}$$

This can be directly integrated to give a total rise T_R for the current I_C to rise from zero to the saturated on-state values I_{CS}:

$$T_R = \int_0^{I_{CS}} \frac{\tau_B}{\frac{\tau_B}{\tau_F} I_{B(on)} - I_C} dI_C \tag{A2}$$

which yields:

$$T_R = -\tau_B \ln\left[1 - \frac{\tau_F}{\tau_B} \frac{I_{CS}}{I_{B(on)}}\right]. \tag{A3}$$

The ultimate limit for which is given when $\tau_F I_{CS}/\tau_B I_{B(on)} \ll 1$ with the approximation $\ln(1 - x) \to -x$, so that:

$$T_R \to \tau_F \frac{I_{CS}}{I_{B(on)}} \tag{A4}$$

$I_{B(on)}$ need only to be for a short pulse (rather than the low hold current). The total charge, $T_R I_{B(on)} = \tau_F I_{CS}$, will still be the same. However, the above arguments assume a steady state base transit time and a neutral base region throughout the switching transient. There is considerable scope to develop fully the theory of turn-on accounting for the reduced base transit time.