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Proposal of Bipolar Transistor Carrier-Injected Optical Modulators and Switches

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A first bipolar transistor optical switch/modulator operated by free-carrier injection is proposed and a theoretical analysis is performed to the structure applied to a DH X-switch. The switching speed of the device can be as fast as 60ps.

Introduction

It has been known that the injection of free carriers into a semiconductor material results in large changes of the absorption coefficient and the refractive index [1]-[4], and several optical modulators and switches with pn(pin) junctions whose operations are based on the application of this phenomenon have been reported. For example, carrier-injected X-switches have been realized recently using InP/InGaAsP [5]-[6].

However, the switching time of such diode-structured optical switches is most often limited by the lifetime of the injected carriers and is, for example, the order of 10^{-8} seconds in GaAs. If a bipolar transistor structure is employed with the injection of carriers into its base, then the methods such as fast-rate removal of stored excess carriers by reverse biasing the base-collector junction, which are frequently applied in practical transistor circuits for high-speed current switching, can also be applied for optical switching at high-speeds. The amplification nature of transistors also means that large emitter or collector switching currents can be controlled by small base currents. Here we propose a first bipolar transistor optical modulator/switch, which is expected to significantly improve the performance of optical modulators and switches which are operated by free-carrier injection.

Analysis

Figure 1 shows one example of our proposal as applied to double hetero-structure TIR X-switches. A single fundamental mode is supported and guided through an n-GaAs layer ($n=10^{17}$cm^{-3} and 0.6μm thick), which is grown between n$-$Ga$_{1-x}$Al$_x$As clad layer ($x=0.15$, $n=10^{17}$cm^{-3} and 0.2μm thick) and n$-$Ga$_{1-y}$Al$_y$As buffer layer ($y=0.05$, $n=10^{17}$cm^{-3} and 4μm thick). An n-p-n GaAs/(GaAl)As heterojunction bipolar

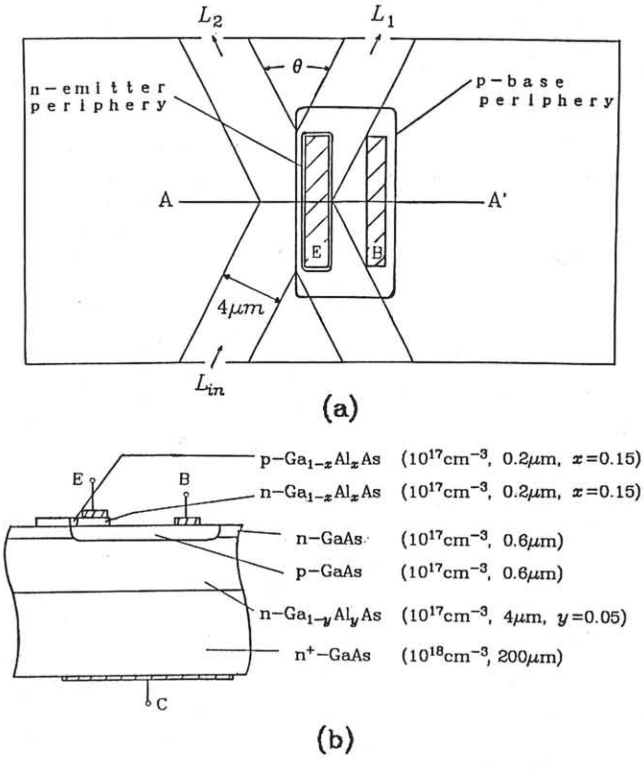


Fig.1 An example of a bipolar transistor optical switch, applied to an X-crossing; (a)overview and (b)AA' cross-section.

transistor is formed around the intersecting region of the two single-mode optical waveguides of $4\mu m$ in width. Here, a part of the n-GaAs waveguide layer and $n-Ga_{1-x}Al_xAs$ clad layer are turned into p-type to form the base layer of the transistor. The collector area is approximately $0.9x10^{-5}cm^2$.

The two-dimensional beam propagation method [7] is applied to determine the behaviour of mode propagation and the switching characteristics of the proposed X-structure. The assumed parameters for the analysis are; the wavelength of 890nm, device length of $800\mu m$, excitation of TE_0-like mode in one of the two input waveguide arms, and negative changes in the refractive index in the base or the waveguide under the emitter area. The index change at the given wavelength would be attributed primarily to the carrier-induced shift of the fundamental absorption edge [1]-[4]. Also the transistor is assumed to operate in its active state when fully turned on, and the internal losses like the absorption are not included in the loss calculations.

Figure 2 shows the calculated switching characteristics for different intersecting angles. For the intersecting angle of $\vartheta=4°$, the propagating beam is switched by the total internal reflection [8] at the emitter current of 150mA and an extinction ratio of better than 14dB is obtained. Typical optical field/power distributions obtained for both the through and crossover states are as shown in Fig.3.

If the angle is increased, such as to the value of $\vartheta=8°$, in order to reduce the switch length, then the required index change Δn as derived from the conditions for total internal reflection will be increased, thereby increasing the required switching current density. Therefore, the switching current cannot be reduced by a profitable amount. A more serious and limiting factor is an increase of the optical radiative losses around the bend for large intersecting angles. For $\vartheta=8°$, the radiative loss is determined to be approximately 1dB in the crossover state, while that for $\vartheta=4°$ is less than 0.5dB. If the angle is reduced,

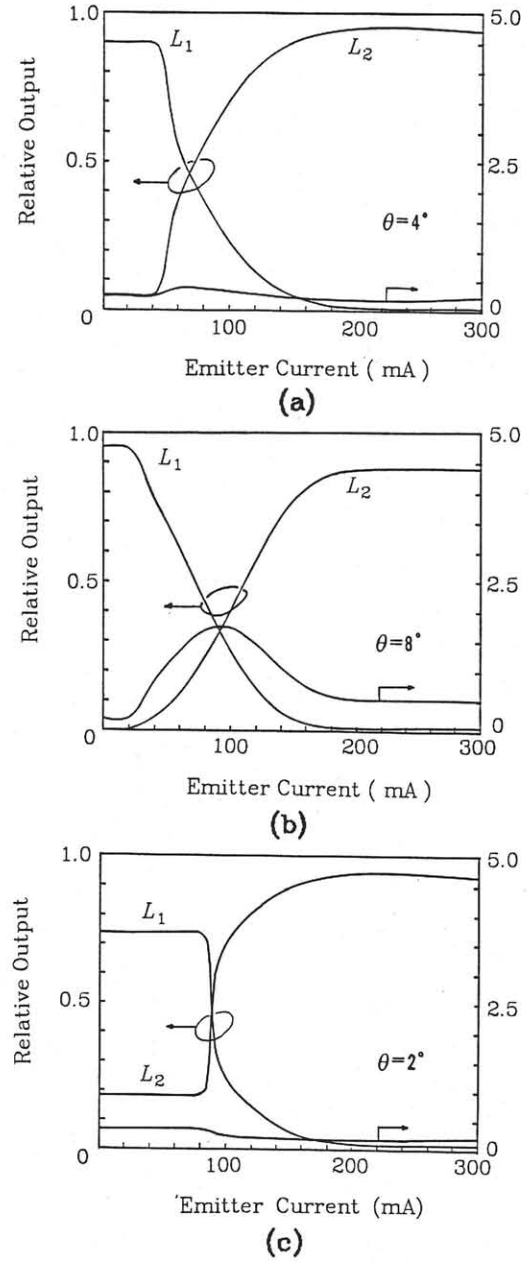
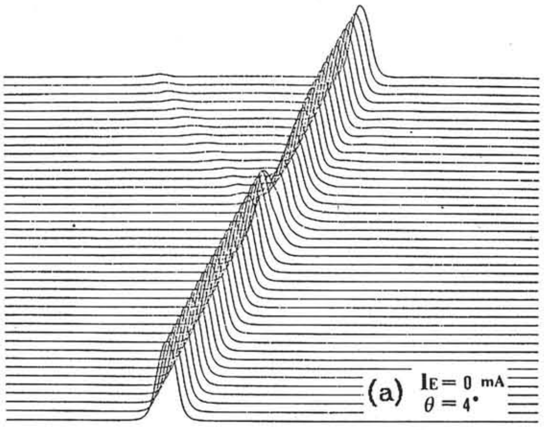


Fig.2 Calculated switching characteristics for (a)$\vartheta=4°$, (b)$\vartheta=8°$, and (c)$\vartheta=2°$.

such as to the value of $\vartheta=2°$, in attempt to reduce Δn , then the resulting increased switch area increases the required switching current. Furthermore, in view of the switching speed, the increased depletion layer capacitance of the base-collector junction is undesirable.

Expressions for the 0-90% rise time t_r and 100-10% fall time t_f of the output



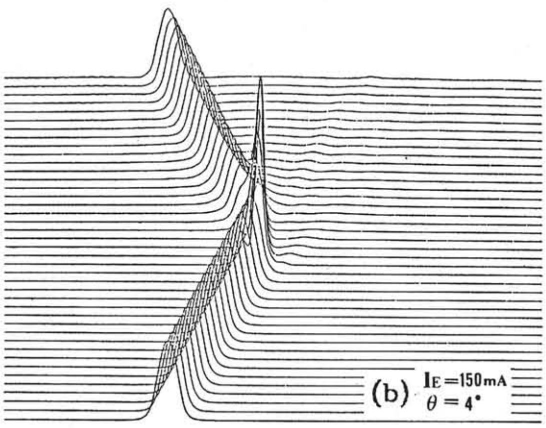
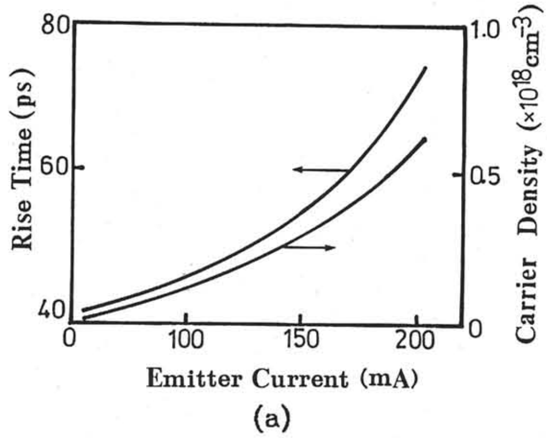


Fig.3 Optical field/power distributions in (a)the through state and (b)the crossover state (ϑ=4°).



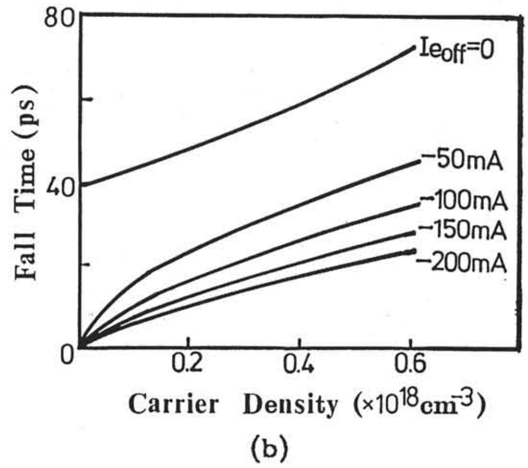


Fig.4 Calculated switching times of the transistor; (a)rise time t_r and (b)fall time t_f.

current when the transistor is driven by a constant input current in the common-base mode, are given approximately by [9]-[12],

$$t_r=\left[\frac{1}{\omega_N}+M\alpha_N C_{ct} R_L\right]\ln\frac{I_{E_1}}{I_{E_1}-\dfrac{0.9I_{C_{on}}}{\alpha_N}}$$

$$t_f=\left[\frac{1}{\omega_N}+M'\alpha_N C_{ct} R_L\right]\ln\frac{I_{C_{on}}+\alpha_N I_{E_2}}{0.1I_{C_{on}}+\alpha_N I_{E_2}}$$

where I_{E_1} and I_{E_2} are the values of emitter current after the turn-on and turn-off step are applied, α_N and ω_N are the normal small-signal active region current gain and cut-off frequency , $I_{C_{on}}$ collector current in on-state, C_{ct} depletion layer capacitance of 0.9pF, R_L load resistance of 50Ω, and M, M' are functions of collector-base voltages and diffusion potential difference between the collector and base. The switching times as a function of input emitter current are plotted in Fig.4, in which the effect of base width modulation is taken into consideration. It is noted that both the t_r and t_f will be approximately 60ps for the required optical switching.

Using a quasi-three dimensional model [13], the magnitude of the optical switching currents can be reduced by an estimate of 30%, if the transistor is operated in the saturation region, where both the emitter-base and collector-base junctions will be forward biased. However, this excess storage of carriers in the base results in an increased switch-off time by the storage time t_s, which for the common-base mode is given by the following expression [9]-[12].

$$t_s=\frac{\omega_N+\omega_I}{\omega_N\omega_I(1-\alpha_N\alpha_I)}\ln\frac{I_{E_2}-I_{E_1}}{\dfrac{I_{C_{on}}}{\alpha_N}+I_{E_2}}$$

where the suffix I represents the inverted state. Figure 5 shows how the

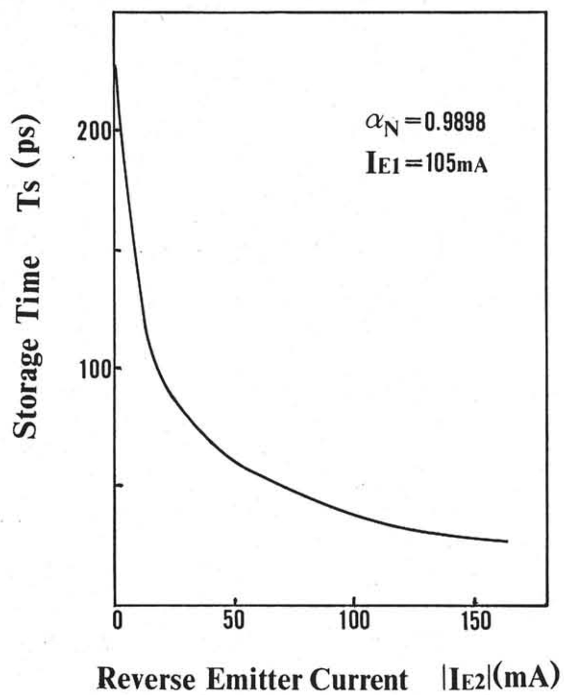


Fig.5 A relationship between the storage time t_s and reverse emitter current I_{E_2}.

storage time t_s can be shortened by applying a large I_{E_2} at the moment of switch-off.

Conclusions

We have proposed a bipolar transistor optical modulator/switch and presented an analysis on the switching characteristics and mode propagation behaviour of the structure applied to a DH X-switch. A charge control analysis shows that the switching time can be as fast as 60ps, which is considerably faster than that for a diode structure. A bipolar transistor structure is expected to be very useful in applications which require optical modulation as well as switching at high frequencies.

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