1000 lasers (i.e., one small area growth) is necessary to produce the number of lasers needed for all of the Si-integrated circuit requirements. The entire array of 1000 lasers can be located on one polyimide transfer diaphragm, and each laser can be aligned with respect to the Si-host substrate and selectively deposited from this diaphragm onto the Si. This will decrease the cost of manufacturing OEIC's since the expensive GaAs devices will only be deposited where needed, and wafer-scale growths can be avoided.

Conclusion

A modified epitaxial liftoff process which utilizes a transparent polyimide diaphragm has been developed to realize the alignable, selective deposition of epitaxial GaAs liftoff material onto host substrates such as Si, glass, and polymers. This transparent diaphragm can be used to align and selectively deposit the GaAs ELO devices as individual devices from the array or as an entire array onto the host substrate. The use of the polyimide transfer diaphragm also allows both the bottom and the top of the device to be processed while under substrate support. With the alignment and selective deposition capabilities inherent in this process, the frugal use of photonic materials is possible, heralding inexpensive, manufacturable OEIC's.

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Wavelength Discriminating Optical Switch

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Abstract—**A novel wavelength discriminating bistable optical switch (WDOS) with completely optical input-output capabilities is presented. The WDOS is a three-terminal AlGaAs/GaAs N-p-n-p structure with an InGaAs/GaAs quantum well light emitting diode at the n-p junction. The WDOS can be switched to stable ON and OFF conditions by optical excitations at different wavelengths which allows the use of a single optical window. The optical switching threshold can be adjusted by the external bias. Depending on the external bias, the WDOS functions as an optical inverter, an electrically programmable optical AND/OR gate, or an all-optical read-write memory element.**

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Introduction

RECENTLY, interests in new device technologies for digital optoelectronic circuits has been mounting. Optical switches will be necessary elements for optical signal processing and digital communication systems. Most of these optoelectronic switches are two terminal p-n-p-n devices similar to the Shockley diode. Several theoretical analyses of p-n-p-n devices have been carried out [1]-[3]. Two terminal switches with optical input and electrical output based on bipolar inversion channel field-effect transistors in the AlGaAs/GaAs [4] and SiGe/Si [5] material systems were demonstrated. An optical inverter consisting of an heterojunction phototransistor (HPT) laterally integrated with an N-p-n-p light emitting diode (LED) has also been realized [6]. We have described the characteristics of an heterojunc-

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tion bipolar transistor (HBT) vertically integrated with a quantum well (QW) LED [7] in a three terminal N-p-n-p structure. The switching characteristics of this device were analyzed under purely electrical and single wavelength optical stimulus. In this letter, we concentrate on the wavelength discriminating optical switching (WDOS) capabilities of this same device. Switching is obtained under illumination by GaAs and He-Ne lasers due to phototransistor action from absorption in the n-GaAs and N-AlGaAs regions, respectively. Strong light emission (ON state) is obtained from the QW LED when the WDOS device is illuminated by a GaAs laser while light emission is suppressed by the He-Ne laser light. The WDOS constitutes a novel vertically integrated all-optical set-reset, input-output optoelectronic switch. Depending on the biasing condition, the WDOS can operate as an optical inverter, an electrically programmable optical AND/OR gate, or an all optical read-write memory element.

Growth and Fabrication

The WDOS layer was grown in a Perkin Elmer 430 molecular beam epitaxy machine on a p^+-GaAs (100) substrate. The layer structure from the substrate up is p-GaAs (0.5 μm, 5×10^{17} cm^{-3}), two 50 Å $In_{0.2}Ga_{0.8}As$ quantum wells surrounded by 100 Å GaAs barriers, an n-GaAs layer (0.1 μm, 5×10^{17} cm^{-3}), an n-GaAs collector (0.5 μm, 5×10^{16} cm^{-3}), a p-GaAs base (0.1 μm, 5×10^{18} cm^{-3}), an N-$Al_{0.25}Ga_{0.75}As$ emitter (0.2 μm, 5×10^{17} cm^{-3}), and an n^+-GaAs cap (0.05 μm, 5×10^{18} cm^{-3}). The band diagram of the WDOS in the OFF-state is shown in Fig. 1 with the various current components noted. The structure can be viewed as interwoven N-p-n and p-n-p bipolar transistors. Standard photolithography and wet etching techniques were used to fabricate devices with various emitter sizes for electrical characterization. Circular devices with emitter windows were also fabricated for optical measurements. Contacts to n- and p-type layers were made by AuGe/Ni/Au and AuBe evaporations, respectively. For optical characterization, an He-Ne (1 mW CW, $\lambda_l = 6328$ Å) and a pulsed GaAs ($\lambda_l \approx 8600$ Å) laser were used and the output spectrum was measured by a photodiode array.

Results and Discussion

Common-emitter current-voltage (I-V) characteristics of the WDOS are given in Fig. 2 for constant base current (I_B) steps. The device functions as an HBT in the low current-low voltage regime (OFF state). The measured collector current is supplied from holes injected from the p^+-substrate (I_{pS}). The electron current injected from the emitter into the collector of the N-p-n transistor (I_{nC}) recombines with the holes (I_{pS}) from the p-n-p device in the InGaAs quantum wells generating light (Fig. 1). The holes from the substrate which do not recombine in the quantum wells as well as the photoregenerated carriers in the depleted collector and neutral base of the N-p-n device create additional base current (I_{pC}) constituting a positive feedback mechanism. The emission energy of the LED was intentionally chosen to be smaller than the GaAs band gap to avoid any feedback resulting from absorption in the N-p-n HBT. In the investigated device, the entire spectrum of the emitted light was verified to be at energies below the GaAs band edge [7]. Thus, we expect the optical feedback to be negligible which allows the switching characteristics of the WDOS to be controlled exclusively by the N-p emitter-base junction bias and the optical inputs. Another advantage of the InGaAs QW LED is that the optical output can be extracted through the GaAs substrate if such a configuration is desirable.

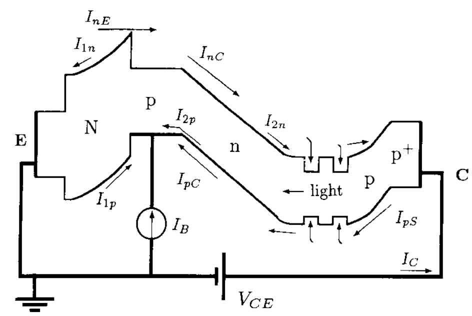

Fig. 1. Band diagram of the WDOS in OFF state. Electron and hole current components are denoted by the subscripts n and p, respectively.

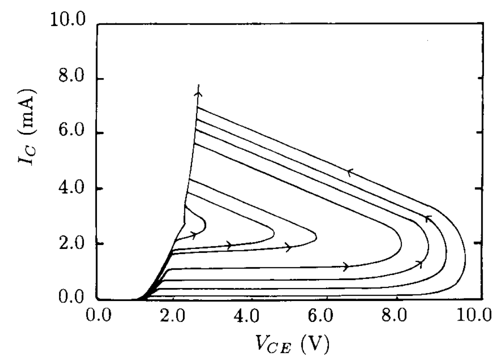

Fig. 2. Current-voltage characteristics of the WDOS (emitter size 10×40 μm). Base current levels are 10, 20, 30, 40, 50, 52, 56, and 58 μA.

In order to understand the switching mechanism, we obtain for the three terminal device, following the notation in Fig. 1 [3], [7]:

$$I_{pS} = \frac{\alpha_N I_B + I_{C0}}{1 - \alpha_N - \alpha_P} \quad (1)$$

where I_{C0} is the saturation current, $\alpha_P = I_{pC}/I_{pS}$ and $\alpha_N = I_{nC}/I_{nE}$ are the respective injection efficiencies (common-base current gains) of the electron and hole currents. The label I_{pS} for the measured collector current was chosen to emphasize that the hole current is supplied by the p^+-substrate in order to avoid confusion with the other current components in the collector of N-p-n HBT. As can be seen from (1), the switch-on condition is reached when $\alpha_N + \alpha_P = 1$. We expect α_P to be much smaller than α_N due to recombination in the InGaAs QW's, and the relatively thick base region, the homojunction emitter, and the emitter-down configuration of the p-n-p transistor. We, therefore, neglect the variation of the relatively small α_P (≈ 0.025 [7])

and consider only the modulation of α_N through the base bias and optical excitation.

In the N-p-n HBT, common-base current gain α_N can be given as [8]

$$\alpha_N = \gamma_N \alpha_T M \tag{2}$$

where γ_N is the emitter efficiency, α_T is the base transport factor, and M is the collector multiplication factor. Under small collector-emitter voltage bias $M \approx 1$. For bipolar transistors with base widths much smaller than the diffusion length, $\alpha_T \approx 1$; and the current gain is given almost entirely by the emitter efficiency, i.e., $\alpha_N \approx \gamma_N$ [8]. For the investigated structure, the base width is sufficiently small (0.1 μm) to justify this approximation.

The emitter efficiency of GaAs HBT's (α_N for our device) increases with increasing base-emitter diode current density, as the contribution of the surface and bulk recombination currents becomes less important compared with the useful diffusion current of minority carriers across the base region [8]. Therefore, the feedback can be controlled by external base bias or optical excitation. Neglecting the recombination of the hole currents from the collector and the external base current in the neutral base, the total base-emitter hole current I_{BT} can be obtained as

$$I_{\mathrm{BT}} = I_B + I_{pC} + I_{2p} - I_{1p} \tag{3}$$

where I_{1p} and I_{2p} are the hole currents due to photogenerated carriers in the N-AlGaAs emitter and in the GaAs p-n base-collector regions, respectively (Fig. 1). Under He-Ne laser (λ_1) excitation, most of the incident light is absorbed in the emitter due to the large absorption coefficient of AlGaAs at this wavelength ($I_{1p} \gg I_{2p}$) resulting in a reduction of I_{BT}. The AlGaAs emitter is transparent to the GaAs laser (λ_2), so in this case photogeneration occurs only in the GaAs base and collector ($I_{2p} \gg I_{1p}$), resulting in increased I_{BT}. Therefore, optical excitations at different wavelengths (λ_1, λ_2) can be used to influence I_{BT} which modulates α_N causing the WDOS to switch ON (λ_2) and OFF (λ_1).

Fig. 3 shows the I-V characteristics of the WDOS as V_{cc} is swept at a constant external base current. The switch-on without the external circuit occurs at the point denoted by I_s and V_s, i.e., switching current and voltage, respectively. The complete circuit, which dictates the particular value of the ON state current level (I_h'), is pictured in the inset. When V_{cc} is swept down from the ON state, switch-off occurs at I_h (the holding current) regardless of the external circuit configuration. The amount of hysteresis between the switch ON and switch OFF current levels is dictated by the external circuit. Load lines 1–3 highlight values of V_{cc} which enable different device functions of the WDOS. We emphasize that the position of these lines is determined by the applied V_{cc} while the slope is determined by the external resistor. Along load line 1 (V_{cc1}), two stable conditions exist at its intercepts (A and B) with the WDOS I-V characteristics. Figure 4 schematically shows the change in the I-V characteristics of the WDOS under illumination by either λ_1 and λ_2, while the inset gives the measured critical current levels at various base biases. Referring to Figs. 3 and 4, we see that when λ_2 is

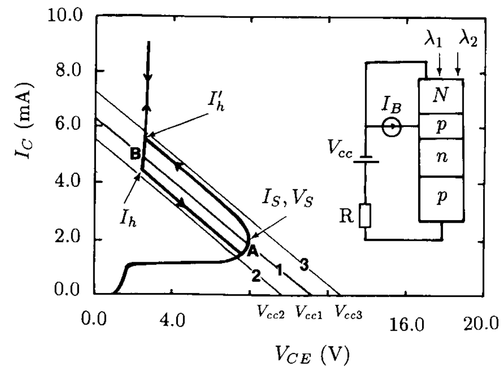

Fig. 3. Current-voltage characteristics of the WDOS (emitter size 10 × 40 μm) as the collector voltage is swept for I_B = 40 μA. The external circuit configuration is shown in the inset (R = 1.8 kΩ). Three interesting load lines obtained for different V_{cc} values are shown as 1, 2, and 3. The switch-on condition is denoted as I_S, V_S where derivative of the current is infinite.

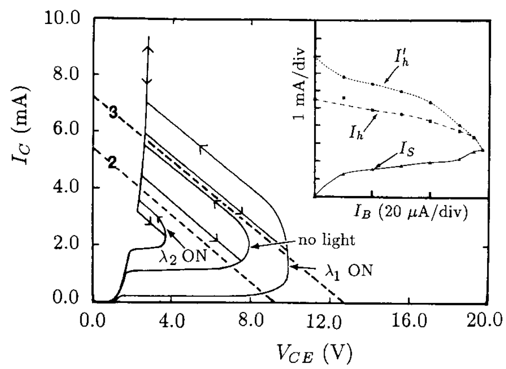

Fig. 4. Schematic I-V characteristics for the WDOS showing the influence of λ_1 and λ_2 illumination. Dashed lines (2 and 3) show the load lines described in Fig. 3. Inset illustrates the actual measured critical current values as a function of I_B.

incident on the WDOS, the new I-V characteristics no longer intersect the load line 1 at point A. The only stable condition is the intercept at point B, so the WDOS switches ON. Point B is common to both curves so that when λ_2 is removed, the WDOS remains in the ON state, illustrating the bistability of the WDOS at V_{cc1}. When λ_1 is incident, point B is no longer an intercept of the new I-V characteristics, and the device must switch to the OFF state. Although we cannot quantitatively measure the input intensities at this time, we have observed that when the devices are electrically biased just below the switching threshold, very weak optical excitations are sufficient to induce switching.

In the case of load line 2 (V_{cc2}), only the OFF state is stable in the absence of an optical input. When the WDOS is illuminated with λ_1, the current levels are further depressed and the device remains OFF. When λ_2 is incident, the device will switch to the ON state. However, the device must return to the OFF state when λ_2 is removed. If both wavelengths are incident, the state will be determined by the relative intensities.

For load line 3 (V_{cc3}), only the ON state is stable. Illumina-

TABLE I
EXPERIMENTALLY DEMONSTRATED LOGIC FUNCTIONS OF THE WDOS. INTENSITY OF THE OPTICAL EXCITATIONS ARE DENOTED WITH $I(\lambda_i)$ AND COMPARISON IS QUALITATIVE. DIFFERENT LOADLINES DEPICTED IN FIG. 3 ARE SHOWN AS V_{cc2} AND V_{cc3}

Input		Output			
		$I(\lambda_1) > I(\lambda_2)$		$I(\lambda_1) < I(\lambda_2)$	
λ_1	λ_2	V_{cc2}	V_{cc3}	V_{cc2}	V_{cc3}
0	0	0	1	0	1
0	1	1	1	1	1
1	0	0	0	0	0
1	1	0	0	1	1
Function		$(\bar{\lambda}_1 \cdot \lambda_2)$	$\bar{\lambda}_1$	λ_2	$(\bar{\lambda}_1 + \lambda_2)$

tion with λ_2 will not affect the ON state. When λ_1 is incident, the value of I_h will be larger than the load line permits and the device will switch OFF. Again, if both wavelengths are incident, the state will be determined by the relative intensities.

Table I summarizes the experimentally observed output states of the WDOS in the form of truth tables which illustrate the logical functions. At V_{cc2}, the WDOS is an AND gate for λ_2 and the inverted λ_1 or a noninverter for λ_2. At V_{cc3}, the WDOS is either an inverter for the λ_1 input or an OR gate for the λ_2 and the inverted λ_1 inputs. In addition to these logic functions, when biased at V_{cc1}, the WDOS is bistable and can be used as a completely optical read–write memory. Because of the different wavelengths of the GaAs laser, He–Ne laser and the QW LED, a single optical window is sufficient. One disadvantage of this particular WDOS design is that in the OFF state, the LED still emits a small amount of light. If the QW LED were replaced by a surface emitting laser structure, the OFF state current levels would lie below the lasing threshold and no light would be emitted.

Conclusions

We have demonstrated a completely optical switch (WDOS) which is capable of discriminating between two distinct input wavelengths and produces a light output. The vertical structure of the WDOS should enable this switch to drive a surface emitting laser output signal. Control of the WDOS switching conditions through modulation of the base current removes the need for large voltages or excitations. Depending on the external bias, the WDOS can operate as an optical inverter, an electrically programmable optical AND/OR gate, or an all-optical read–write memory element.

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