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Optical Bistable Devices by Charge-Induced Self-Feedback: Switching Time and Spatial Resolution

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We present experimental positive proofs of some of unique characteristics which recently proposed novel optical bistable devices (Charge-Induced Self-Feedback Devices : CSFDs) offer: 1) a fast switching time free from a CR time constant and 2) independent operations of the individual devices by means of the spatial separation of incident light beams (a spatial resolution). An in-plane spreading of photo-excited carriers which limits the spatial resolution of the CSFD is briefly theoretically discussed.

1.INTRODUCTION

In recent years, a wide class of optical bistable devices[1)2)] with GaAs/AlGaAs multiple quantum well structures (MQWS) have been proposed as promising optical switching devices. Among the devices of this kind, a novel optical bistable device named Charge-Induced Self-Feedback Device (CSFD)[3)] has a variety of unique characteristics as follows. Since this device functions based on the combination of quantum confined Stark effect (QCSE)[4)] and charge-induced self-feedback[5)] due to the field-screening in MQWS, no additional external circuit element, such as a series resistor, is required, leading to a great simplicity in the integration of two-dimensional chips. The existence of the optical bistability due to the above-mentioned mechanisms has already been demonstrated experimentally. Other epoch-making features of the CSFD which remain to be experimentally confirmed are 1) that a switching time is not restricted by a CR time constant and 2) that the devices can be driven independently in terms of a spatial separation of incident light beam spots with no pixelled structures. Therefore, the aim of the present work is to present experimental confirmations for the above advantages in the CSFD.

2.SAMPLE STRUCTURE AND OPERATING PRINCIPLE

The device used in this experiment is a *p-i-n* diode with a 20-period GaAs (Lz=90Å)/$Al_xGa_{1-x}As$ (x=0.2 and L_B=100Å) MQWS. The MQW layer is sandwiched between two outer side barrier layers of a 500 Å undoped $Al_{0.45}Ga_{0.55}As$ layer at *n*-side and a 80 Å undoped AlAs layer at *p*-side so that photo-excited carriers can be efficiently accumulated at the edge of the MQW.

The optical positive self-feedback in the CSFD can be achieved as follows.[5)] A reversely biased device is illuminated by an optical beam with a wavelength slightly shorter than an initial optical absorption line. Increase in the optical input power leads to the accumulation of electron and hole charges at the edge of MQW layer and the charges screen the original electric field within the MQW. The field-screening shifts the optical absorption line towards a shorter wavelength so that the optical absorption increases.

3. SWITCHING TIME

Turn-on and turn-off times of the CSFD are respectively determined in the following way. The turn-on time is determined by the time (τ_f) it takes the positive feedback mentioned before to complete and the turn-off time is determined by the time (τ_l) it takes photo-excited carriers to escape out of the MQW layer.

Figure 1 shows time-resolved differential absorption coefficients for different optical input powers obtained by a pump-probe measurement performed with 6 psec.-optical pulses. The built-up time (τ_b) of the charge polarizations is about 50 psec.. The τ_b gets shorter with increasing the input powers because a higher carrier excitation leads to a speedy accumulation of the charges at the interface. As mentioned before, the turn-on time should be determined by τ_f , not only by τ_b since it takes sometime an overall feedback process to complete after τ_b. However, we conclude that the turn-on time is about same order of τ_b because the τ_f is considered to be limited dominantly by τ_b.

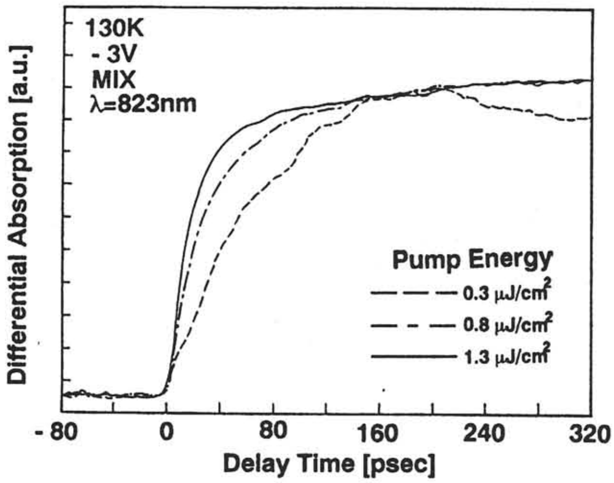

Figure 1 Time-resolved differential absorption for different optical input powers obtained by a pump-probe measurement performed with 6 psec.-optical pulses.

In order to obtain the turn-off time, the time-resolved photocurrent (PC) measurement with the optical pulse whose width is ~ 6 psec.. Figure 2 shows the time-resolved photocurrent results as a function of a reverse bias. The decay time of the PC decreases with increase the reverse bias. This implies that the decay time corresponds to τ_l because the field-induced modification of potential barriers located at the interface makes photo-excited carriers leak more quickly. We obtained τ_l = ~2 psec. under the reverse bias of ~ 8V.

From the above results, the overall switching time is limited by the turn-off time which is about several nsec. in the devices used in the present work.

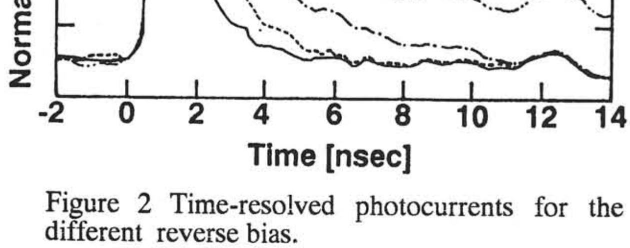

Figure 2 Time-resolved photocurrents for the different reverse bias.

4. SPATIAL RESOLUTION

Samples are illuminated by light beams with a wavelength of 850 nm under the reverse bias of -6V. Figure 3 shows the optical input power dependence of photocurrents at room temperature. The upper and lower curves correspond to the case with two beams spatially separated by a distance of ~ 500 μm and the case with the only one beam (Beam1), respectively. A comparison between these results leads us to the most desired conclusion in the present work that the CSFD can be driven with no serious influence of the other beams separated by a certain distance.

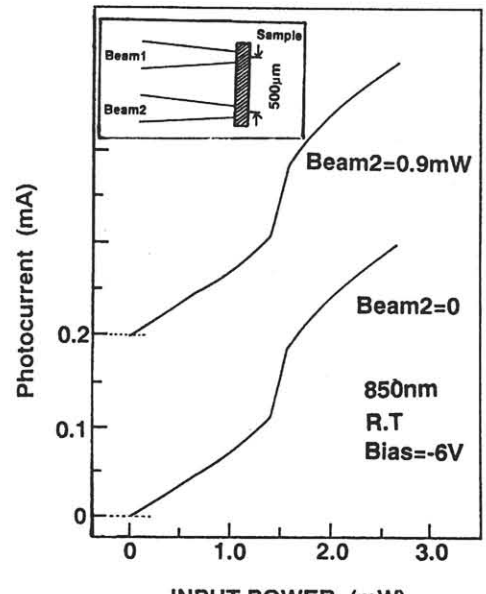

Figure 3 Photocurrents as a function of the incident light power of the Beam1 at room temperature.The upper and lower curves correspond to the case with two beams spatially separated by a distance of ~ 500 μm and the case with the only one beam (Beam1), respectively.

A question of what determines the distance, in other words, a spatial resolution of the CSFD, naturally arises. In search for a clue to the question, we performed a measurement of the beam spot size dependence of switching powers. Figure 4(a) shows input power vs. photocurrent characteristics for different beam spot sizes. The switching power decreases with a reduction in the spot size. In order to make more careful inspection of a relation between the switching power and the spot size, it might be of great help to plot switching powers as a function of a beam spot area as shown in Fig.4 (b). Provided photo-excited carriers piled up at the interface do not spread at all in a lateral direction (along the interface), the switching power should be directly proportional to the spot area as shown by a dashed line. The experimental data, however, deviate upward from a dashed straight line and the deviation apparently gets larger as a spot area gets smaller. This suggests that an in-plane spreading of photo-excited carriers exists and also that a ratio of the size of the spreading to the spot size increases as the spot size is reduced. Moreover, the latter suggestion might lead us to the conclusion that the spatial resolution of the CSFD is limited primarily by a beam spot size for a larger spot and by the in-

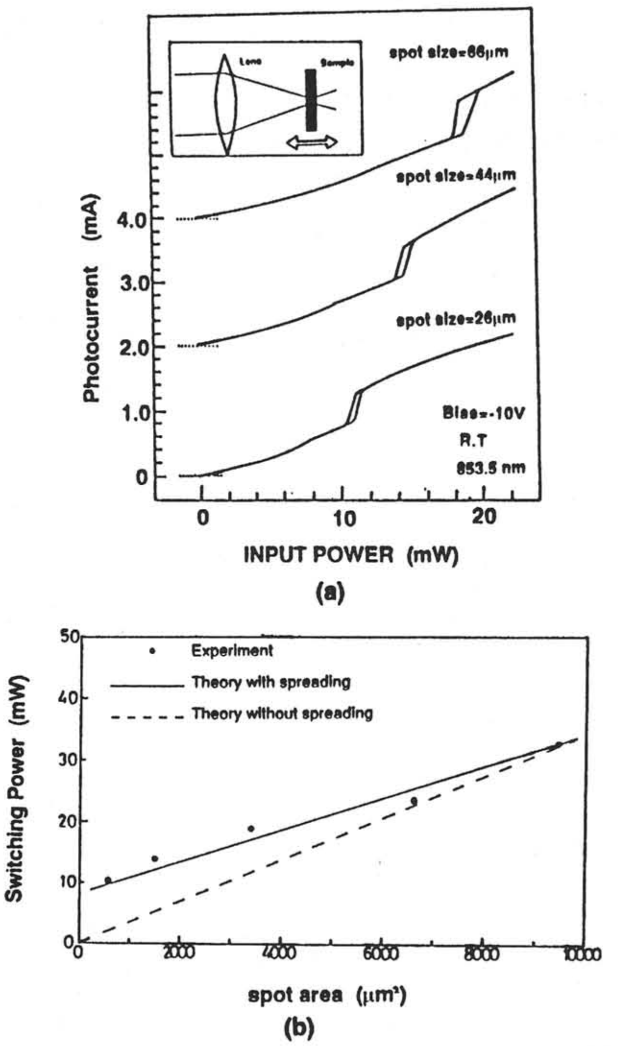

Figure 4 (a) Photocurrents as functions of the incident light power at room temperature for different beam spot sizes. (b) Dots show the experimental results on the optical switching power as a function of a beam spot area. A dashed and solid lines show theoretical results on the optical switching power as a function of a beam area without and with in-plane carrier spreading,respectively.

plane carrier spreading length for a smaller spot, respectively.

Next, we performed a theoretical study of the in-plane carrier spreading by using the coupled equation of drift-diffusion equations for electrons and holes taking into account of an effect of the transverse electric field originating from the potential difference between excited and un-excited regions.[6] The coupled equation was numerically solved using parameters most of which are obtained by measurements, such as beam spot sizes, input powers and a carrier leak time: τ_l ~ several nsec.. A theoretical value of the in-plane carrier spreading length is 25μm for the case where a beam spot size =26μm, an input power =11mW and τ_l =3 nsec.. This agrees well with the experimental result: ~30μm. It is worth while noticing that a theoretical value of the spreading length, obtained by the coupled drift-diffusion equation without the effect of the transverse electric field, is 1.6μm. A calculated spot size dependence of switching powers also agrees well with experimental data (see solid line in Fig.4(b)). From these facts, the transverse electric field seems to be primarily responsible for a large in-plane carrier spreading.

Such a large in-plane carrier spreading is undesirable and has to be suppressed as much as possible to achieve a better spatial resolution . We theoretically found that the suppression of the in-plane carrier spreading can be obtained by a reduction in a carrier leak time: τ_l. For example, if τ_l is reduced down from 3nsec. to 100psec. in the above case, the spreading length can be suppressed from 25μm to 2.5μm.

5. SUMMARY

We reported the experimental results on a switching time and a spatial resolution of the CSFD. The switching time obtained in the present work is as fast as about several nsec.. It is demonstrated that the independent operation of the CSFDs is certainly possible in term of a spatial separation of the incident beam spots. We also found that a large in-plane carrier spreading ,which makes the spatial resolution poor, takes place. Judging from a comparison between a theory and an experiment, such a large in-plane carrier spreading is primarily driven by the transverse electric field originating from the potential difference. The reduction of the carrier leak time τ_l is theoretically proposed to suppress the in-plane carrier spreading.

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