Three steps modeling of transient voltage balance in a self-electro-optic effect device based on the potential function theory

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1. Introduction

The electro-optical absorption characteristics in semiconductor quantum well structures are interesting for optical devices applications. The negative differential conductance (NDC) characteristics of the quantum well diodes are useful for the operation mechanism of symmetric self-electro-optic effect devices (S-SEED's) which are attractive in achieving optically bistable and/or multistable devices [1,2].

In superlattices (SL's) under electric fields, the following distinct modulation can be obtained in transmission versus voltage (T-V) characteristics by the so-called Wannier-Stark localization (WSL) mechanism [3,4]. Firstly, a low-loss transmission state is achieved by the blue-shift mechanism of the optical absorption edge. Secondly, additional absorption peaks develop owing to the successive resonances to the Stark-ladder transitions. Such T-V characteristics cause multiple NDC regions in photocurrent versus voltage (PC-V) characteristics, which is useful to obtain the multistable operation in simple SEED configurations [5,6]. Previously, we showed that stable operating states in multistable SEED's are determined by using a potential function [7]. However, no details have yet been shown of the temporal variations of the operating voltages under optical excitation. In this paper, we elucidate transient responses and resultant steady states of the optical pulse excited SL-S-SEED by three steps modeling.

2. Equivalent circuit of the SEED

Figure 1 shows the equivalent circuit of the optical pulse excited SEED reverse-biased by V_S assuming a constant capacitance (C_d). Diode D_1 (D_2) was illuminated by both a cw signal light S_1 (S_2) and a pulsed control light C_1 (C_2).

An SL sample consisting of 100-period GaAs/AlAs layers was grown on an n-type GaAs (001) substrate by molecular beam epitaxy (MBE). The nominal GaAs well width was L_Z=3.13 nm and the AlAs barrier thickness was L_B=0.57 nm. The sample was processed to form 900-μm-square mesa diodes with a 200-μm-circular optical window, and a part of the GaAs substrate under the mesas was removed to enable transmission. Details of the diode structure have been described in our previous paper [8] and will not be repeated here.

3. Theoretical analysis of stable operating points

We briefly summarize the theoretical analysis of switching mechanisms of the S-SEED based on the potential function theory [7]. We consider the generated photocurrent in the n-th diode to be given by,

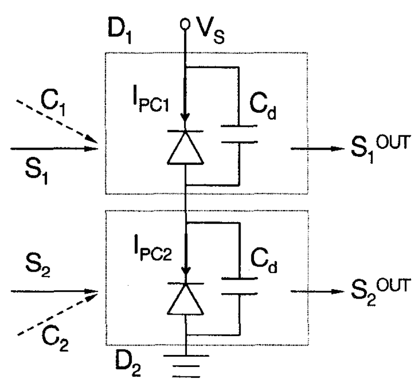

Fig. 1: Equivalent circuit of an S-SEED biased by V_S consisting of two SL diodes assuming a constant capacitance (C_d) for each diode.

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$$I_n = P_n \cdot I_{Sn,\lambda}(V_n) \qquad (n = 1 \text{ or } 2) \tag{1}$$

where $I_{Sn,\lambda}$ denotes the PC-V characteristics under the cw illumination of S_n at wavelength λ, which is given as a function of the applied bias voltage to the diode (V_n), and P_n is the ratio of the optical power to the bias light S_n.

The current continuity in the SEED is described as

$$I_1 + C_d \frac{dV_1}{dt} = I_2 + C_d \frac{dV_2}{dt}. \tag{2}$$

Using notations $V=V_2$ and $V_s-V=V_1$, we obtain

$$\frac{dV}{dt} = \frac{1}{2C_d}\left(P_1 \cdot I_{S1,\lambda}(V_S - V) - P_2 \cdot I_{S2,\lambda}(V) \right) \tag{3}$$

A potential function $\partial U_{P1,P2,\lambda}(V)$ is defined [7]

$$\frac{dV}{dt} = -\frac{\partial U_{P1,P2,\lambda}(V)}{\partial V} \tag{4}$$

and then,

$$U_{P1,P2,\lambda}(V) = \frac{1}{2C_d}\int_0^V \left(P_1 \cdot I_{S1,\lambda}(V_S - V') - P_2 \cdot I_{S2,\lambda}(V') \right) dV' \tag{5}$$

By the potential function theory, the stable points in steady state are descried by the local minima in the potential function given by equation (5). In addition, the gradients of the potential function indicate directions to new stable operating points. As shown by equation (5), the potential function is determined by the numerical integration of the PC-V characteristics of the diodes. Therefore, the operating characteristics of the S-SEED can be controlled by an amount of the photogenerated charges.

4. Results and discussion

Potential function curve

Figure 2(a) and 2(b) show measured T-V and PC-V characteristics of diode D_1 under illumination of 767 nm. The other diode shows almost the same characteristics. Negative values for the abscissa refer to reverse bias voltages. Figure 3 shows calculated potential functions for the SL-SEED at different optical power ratios, which were determined by the numerical integration of the PC-V characteristics of the diodes. The ratio, hereafter called the power coefficient, is defined by $n = \log_{0.9}(P_1/P_2)$, where the base of the logarithm is selected arbitrarily.

The dotted lines in Fig. 3, labeled by A, B, and C, are guides for the eye to indicate the local minimum positions of the potential function curves. Stable operating points on the T-V curves, which is corresponding to the three local minima, are indicated by the same symbols in Fig. 2(a). The transmission intensity levels at the operating points are

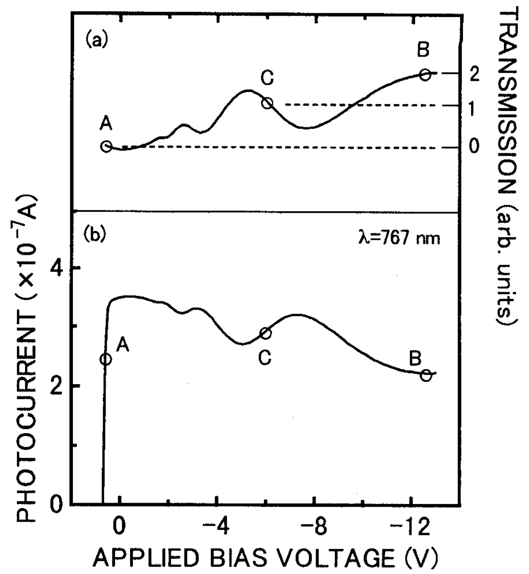

Fig. 2: (a) Transmission versus voltage (T-V) characteristics of diode D_1. (b) Photocurrent versus voltage (PC-V) characteristics of diode D_1.

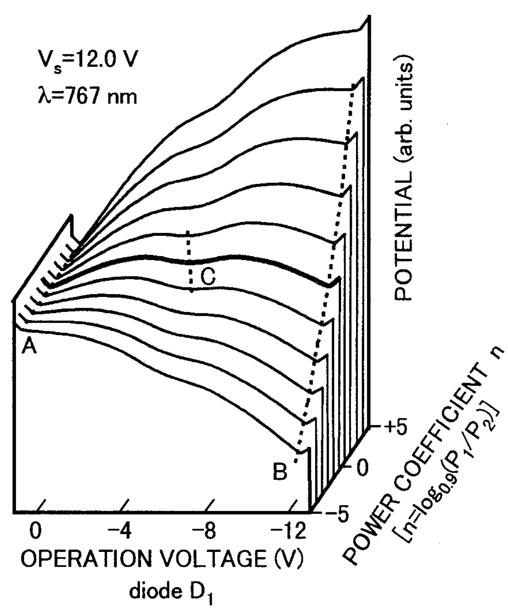

Fig. 3: Calculated potential curves plotted as a function of the relative excitation intensity (power coefficient, n). The dotted lines are guides for the eye to show the local minima of the potential curves.

denoted by 0, 1, and 2 on the right axis.

When the power coefficient is zero ($P_1=P_2$, depicted by the thick line), there are three local minima in the potential curve. If the initial operating voltage to diode D_1 is 0 V, namely the operating point is A, the power coefficient of n<-5 is required to release the operating point from the initial state. Under this excitation condition, however, the intermediate local minimum at C, disappears. Consequently, the operating point moves to the other local minimum at V_1 = -12 V, namely the operating point B. Obviously, the excitation condition of n>5 sets back the S-SEED to the initial state. Such switching of the operating point results in bistable operation. However, during the switching process at a certain timing the operating voltage crosses the bias condition corresponding to the intermediate stable state. By terminating the excitation pulse at this timing, a tilted potential curve ($|n|\approx 5$) will recover the initial potential profile (n=0). As a result, the operating point will settle down to the intermediate local minimum position. This potential controlling procedure can be achieved by supplying an adequate photogenerated charge tuned by the optical pulse width and/or height.

Transient optical responses: three steps model

We have measured the optical responses of the S-SEED to optical pulses with different heights but the same width of 100 μs. Figure 4 shows one of the optical responses. Figure (a) shows the temporal responses during the optical excitation, while Fig. (b) shows the response after the excitation. The excitation timing is indicated by the bottom traces. The upper traces labeled by S_1^{OUT} and S_2^{OUT} represent optical outputs from diodes D_1 and D_2, respectively. The transmission intensity levels indicated by 0, 1, and 2 correspond to those of Fig. 2(a). By the optical pulse excitation, the output intensity of diode D_1 (D_2) is switched from state 0 (2) to state 1 (1). This shows that the voltage balance of the diodes reaches the intermediate local minimum region on the n=0 potential curve.

By comparing the optical responses of Fig. 4(a) and the T-V curves of Fig. 2(a), we can determine the temporal voltages. In the initial and final states, the applied bias voltages keep their total voltage to a constant value V_S, i.e., $V_S=V_1+V_2$. Hereafter, we call this condition an equilibrium state. While during the excitation, namely, the first step of the optical responses, we note that the total value of the temporal voltage is not equal to the applied voltage, i.e., $V_S \neq V_1'+V_2'$. We call this condition a nonequilibrium state. This is because the capacitors of the S-SEED require a finite time to charge and/or discharge the diodes. In other words, it seems that excess photogenerated charges in the excited diode reduce the reverse bias voltage to the diode. However, after the excitation shown in Fig. 4(b), this nonequilibrium state quickly (less than 1 ms) recovers the equilibrium state. This recovering process is the second step of the optical response.

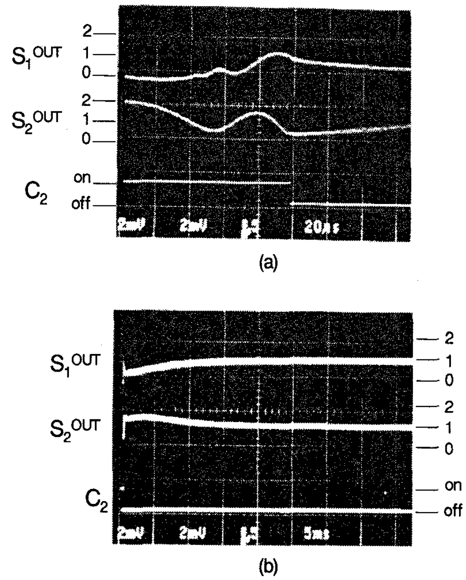

Fig. 4: Transient optical responses of the S-SEED; (a) 20 μs/div and (b) 5 ms/div. The upper traces S_1^{OUT} and S_2^{OUT} represent the transmission signals of diodes D_1 and D_2, respectively. Labels 0, 1, and 2 correspond to the transmission intensities shown in Fig. 2(a). The lower schematic trace, C_2, indicates the electrical signal to generate the optical pulses to diode D_2.

To determine the resultant equilibrium states evolved from the temporal nonequilibrium states, we assume that each diode is supplied the same amount of electrostatic energy in the recovering process. In this process, the operating points of the diodes (V_1',V_2') move on the PC-V curves when the power coefficient is zero ($P_1=P_2$) and reach to the equilibrium states (V_1,V_2) in a short time. Namely, the voltages V_1', V_2', V_1, and V_2, satisfy the following equations,

$$\begin{aligned} &\int_{V_1'}^{V_1} I_{S1,\lambda}(V')\,dV' = \int_{V_2'}^{V_2} I_{S2,\lambda}(V'')\,dV'' \\ &V_S \neq V_1'+V_2' \\ &V_S = V_1+V_2 \end{aligned} \qquad (6)$$

We obtained the values for V_1 and V_2 corresponding to the arbitrary sets for (V_1', V_2') by numerical calculation. In Fig. 5, the arbitrary nonequilibrium states are represented by the coordinates V_1', V_2', and the equilibrium conditions are indicated by the dashed line. The equilibrium condition is divided into three segments by the two small dots corresponding to the local maxima of the n=0 potential curve (the dashed curve). The segments I, II, and III contain the local minima A, C, and B, respectively. According to the positions (the segments I, II, and III) of the calculated equilibrium states, the original nonequilibrium states are divided into three regions labeled by I', II', and III'. The solid curves show the boundaries of the regions.

Once the temporal operating point reaches the equilibrium condition, the operating point settles down into the local minimum of the potential curve. This is the third step.

Finally, in Fig. 5, we plotted the experimental responses to the optical pulses whose relative intensities to the weakest pulse were 1.0 (about 100 μW), 1.5, 1,6, 2.0, 2.5, 2.9, and 5.0 (seven symbols from the left side). The down triangles, open circles, and up triangles indicate the switchings from state 0 to 0, from 0 to 1, and from 0 to 2, respectively. The switching processes when the relative intensity is 2.5 are shown by a set of three arrows (the optical responses are shown in Fig. 4). The dash-dotted arrow, dotted arrow, and dashed arrow indicate the excitation process, recovering process, and settling down process, respectively. The experimental results agree with the theoretical prediction based on the three steps modeling.

5. Conclusion

We have investigated, experimentally and theoretically, transient optical responses and steady states of the SL-S-SEED controlled by optical pulses. It has become clear that the switching mechanism of the pulse-excited S-SEED consists of three successive processes.

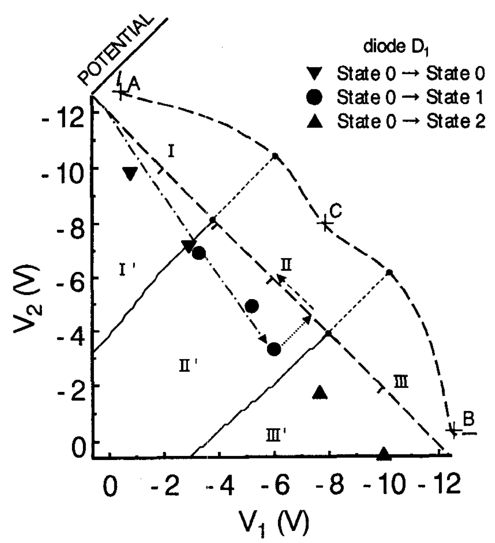

Fig. 5: Voltage-balance graph of diodes in switching processes. The down triangles, solid circles, and up triangles indicate the experimental temporal voltages at the end of the excitation pulses with different intensities. The dashed line indicates the voltage equilibrium state. The dashed curve represents the potential function without optical pulse excitation. The local minima (shown by crosses) of the potential function correspond to the stable states A, B, or C. Theoretically, the nonequilibrium states shown by I', II', and III' are recovered to the equilibrium states labeled by I, II, and III, respectively.

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