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Optoelectronic Flexible-Function Logic Gate Using Monostable-Bistable Transition of Serially Connected Resonant Tunneling Transistors

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1. Introduction

Resonant tunneling devices have been studied for ultra-high frequency applications [1], and high-speed and functional logic applications [2], because of their high-speed response and functionality due to the negative-differential-resistance (NDR) characteristics. Recently, the logic gate, MOBILE (monostable-bistable transition logic element) [3], which exploits the NDR of the resonant tunneling transistors (RTTs), have been developed into highly functional logic gates [4] and high-speed flip-flops [5].

We have recently reported the optoelectronic application of the MOBILE [6]. The proposed optoelectronic (OE) logic gate, OE MOBILE, is characterized by optically controlled bistability and high sensitivity to an optical input owing to an operation based on the monostable-bistable transition.

In this report, we demonstrate a successful operation of the flexible-function logic of the OE MOBILE for optical inputs. Different functions such as NOR, NAND, OR, and AND for two optical inputs are confirmed in a single logic gate.

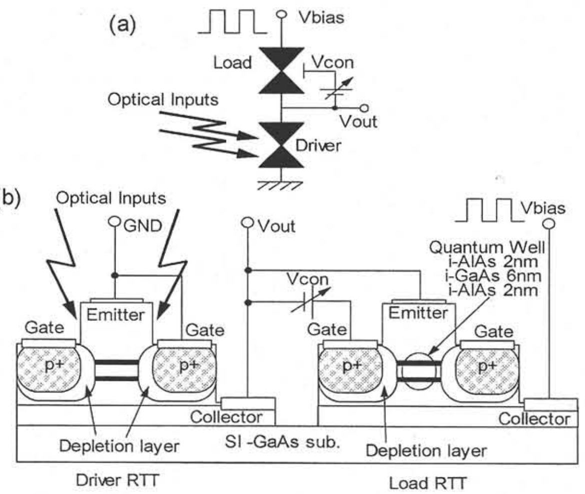


Fig. 1 (a) The circuit configuration and (b) the schematic image of a OE MOBILE consisting of two resonant tunneling transistors connected in series.

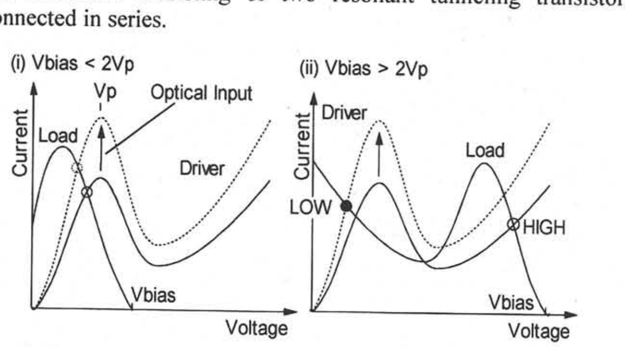


Fig. 2 The load line diagrams of the OE MOBILE (i) at $V_{bias} < 2\ V_p$ and (ii) at $V_{bias} > 2\ V_p$.

2. Device Structure and Operation Principle

Figure 1 shows (a) the circuit configuration and (b) the schematic cross section of an optoelectronic monostable-bistable transition logic element (OE MOBILE) consisting of two RTTs connected in series. An i-AlAs/i-GaAs/i-AlAs resonant tunneling structure (2/6/2 nm) was sandwiched between n-GaAs emitter/collector layers. The junction gate shown in Fig. 1(b) controls the width of the depletion layer and hence the transistor current. To use monostable-bistable transition, the circuit is driven by an oscillating bias voltage (V_{bias}) [3]. The optical inputs are applied by illuminating the driver RTT in order to increase its peak current (I_p). The control terminal voltage (V_{con}) is applied to the p^+/n-junction gate of the load RTT to control its I_p, which determines the logic function of the OE MOBILE. The gate voltage (V_g) of the driver RTT is set to be zero volts. The output voltage (V_{out}) is monitored through the node between two RTTs.

Figure 2 shows the load-line diagrams of the OE MOBILE. The broken and solid lines for the driver RTT show the currents with and without optical inputs, respectively. There is one stable point at (i) $V_{bias} < 2\ V_p$ (monostable), and two at (ii) $V_{bias} > 2\ V_p$ (bistable). Monostable-bistable transition occurs at $V_{bias} = 2\ V_p$. The output level is determined by the relative value of the I_p's of the driver and load RTTs. For example, a smaller I_p of the driver RTT without an optical input results in high-level output voltage as shown by the open circle in Fig. 2 (ii). When the I_p of the driver RTT is increased to a value larger than the I_p of the load by applying optical inputs, a low-level output voltage is obtained, as shown by the closed circle. The RTTs play both roles of a photodetector and a logic transistor.

The OE MOBILE is expected to have the following advantages. The switching operation can be achieved even if the input light power is very small because the relative I_p value between the two RTTs determines the output level. Moreover, the logic function of the OE MOBILE is programmable by changing V_{con} which controls the I_p of the load RTT. The detail will be discussed in the next section.

3. Experimental Results

Figure 3 shows the collector current-voltage characteristics of a RTT with and without light illumination at the gate voltage of zero volts. The power of the optical input illuminating the RTT was 10 μW. The increase in the peak current of RTT is 96 μA when the optical input of 10 μW was applied. The effective responsivity is 9.6 A/W at the peak voltage of 0.315 V. The value is larger by a factor of 10 than that expected for an ideal photodiode, λ/1.24 (A/W). Here, λ is the wavelength of the incident light with unit of micrometer. The large responsivity is probably due to the field-effect amplification of photo-excited carries by a p^+/n-junction gate.

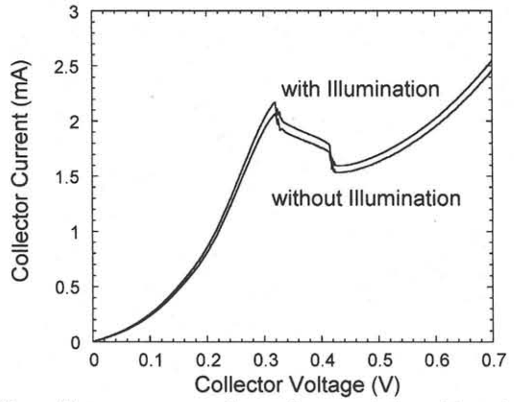


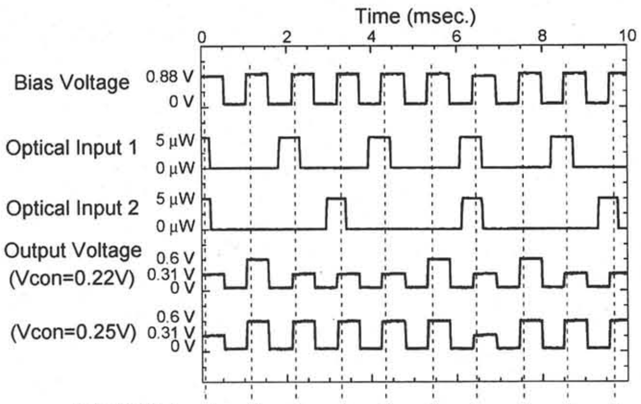
Fig. 3 The collector current-voltage characteristics with and without the illumination at $V_g = 0$ V. The incident optical power is 10 μW.

Figure 4 shows the results of NOR and NAND operations together with the truth table of the gate. The traces show, from top to bottom, the bias voltage, the optical inputs of 1 and 2, and the output voltages at $V_{con} = 0.22$ V and 0.25 V. Two optical inputs were applied to the driver RTT using two lightwave probes consisting of a single-mode fiber with a lensed tip. It should be noted that V_{con} determines the function of the OE MOBILE. At $V_{con} = 0.22$ V, the output voltage becomes high only when both optical inputs, 1 and 2, are low. This demonstrates that the logic gate performs a NOR operation. At $V_{con} = 0.25$ V, on the other hand, the gate performs a NAND operation. The output voltage becomes low only when both optical inputs, 1 and 2, are high as shown in the figure. At $V_{con} = 0.22$ V, I_p difference between the driver and load RTTs is small. Therefore, one optical input is sufficient to increase the I_p of the driver over the I_p of the load, resulting in the NOR operation. When the I_p of the load is increased by increasing V_{con} from 0.22 V to 0.25 V, two optical inputs are necessary to change the logic level of the gate. This corresponds to the NAND operation. These results show that the OE MOBILE has the advantage that both NOR and NAND operations can be performed in the same logic gate. Moreover, it should be noted that the output voltage remains at a low level even when the optical input is turned off while the bias voltage is applied. This latching behavior stems from the bistable operation of the present logic gate. By applying the optical inputs to the load RTT, it was possible to realize both OR and AND operations because, in this case, the through function instead of inverter function was available as shown in Fig. 5 for $V_{con} = -0.19$ and $V_{con} = -0.17$ V.

These results means that the present OE MOBILE has a potential of majority-logic-function for multiple optical inputs with both signs.

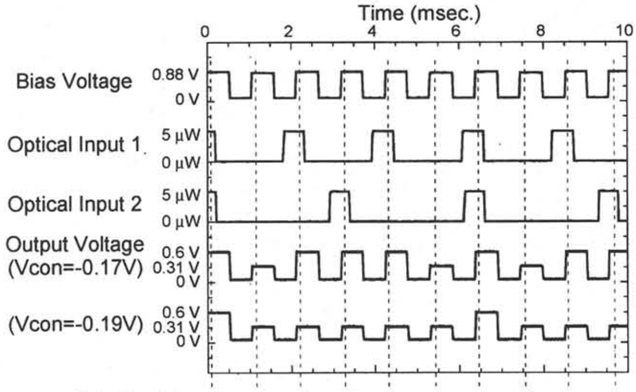
4. Conclusions

Optoelectronic functional logic gate consisting of serially connected resonant tunneling transistors has been successfully demonstrated. The gate which has the advantages of the flexible logic with latching behavior will provide a new approach to optical data processing.



Optical Input 1	1	0	1	0	1	0	1	0	1	0
Optical Input 2	1	0	0	1	0	0	1	0	0	1
Output Voltage Vcon = 0.22 V	0	1	0	0	0	1	0	1	0	0
Vcon = 0.25 V	0	1	1	1	1	1	0	1	1	1

Fig. 4 The traces of NOR and NAND operations together with the truth table of the OE MOBILE. They are, from top to bottom, the bias voltage, the optical input 1, the optical input 2, the output voltage at $V_{con} = 0.22$ V, and the output voltage at $V_{con} = 0.25$ V.



Optical Input 1	1	0	1	0	1	0	1	0	1	0
Optical Input 2	1	0	0	1	0	0	1	0	0	1
Output Voltage Vcon = -0.17 V	1	0	1	1	1	0	1	0	1	1
Vcon = -0.19 V	1	0	0	0	0	0	1	0	0	0

Fig. 5 The traces of OR and AND operations together with the truth table of the OE MOBILE. They are, from top to bottom, the bias voltage, the optical input 1, the optical input 2, the output voltage at $V_{con} = -0.17$ V, and the output voltage at $V_{con} = -0.19$ V.

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