Photo-Controlled MOBILE's*

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Abstract: A novel optoelectronic functional circuit with heterojunction phototransistors (HPTs) and resonant tunneling diodes (RTDs) is described, which presents the function of both photocurrent switching and photo-current latching. These behaviors have been demonstrated by simulating experiments and circuit simulation. Furthermore, basing on photo-current latching behavior, various photo-controlled basis logic elements such as delayed flip-flop (DFF) can be designed and fabricated.

Key words: monostable-bistable transition logic elements; photo-controlled; simulation

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1 Introduction

The resonant tunneling diode (RTD)[1] is a high-speed nanoelectronic device based on quantum resonant tunneling effect. It has the advantages of high speed, high frequency, low operating voltage, low power dissipation, intrinsic bistablity, and self-latching due to its negative differential resistance. Compared with conventional devices, it also has the feature of reducing the device count for achieving the same logic function.

The monostable-bistable transition logic elements (MOBILE's[2]) are formed with two RTDs connected in series. MOBILE's have several advantages such as multiple inputs and multiple functions. They can perform threshold logic functions on the weighted sum of input signals and flexible logic circuits, etc.

If we replace the HEMT in a MOBILE's with a photo-detector, the MOBILE's can be photosensitized and become the photo-controlled MOBILE's. From the different kind of the photo-detector, the photo-controlled MOBILE's are also divided into several types such as RTD/MSM, RTD/PIN, RTD/UTC-PD[3], and RTD/HPT photo-controlled MOBILE's. Among these types of photo-controlled MOBILE's, RTD/HPT (heterojunction bipolar phototransistor) structure is better than others because it has following advantages. (1) HPT has large enough output photocurrent (in mA current level) that can be matched with RTD; (2) Compared with photo-diode, there is a optical gain for HPT. Therefore, HPT can provide a suitable output current for a less input of light power; (3) HPT has high switching speed and high frequency of 3dB; (4) In the fabrication of HPT, the thickness of base region can be controlled in nano-meter scale accurately by MBE or MOCVD technology. So, its performance can be controlled easily; (5) The material structure for both the high performance RTD and the HPT used for optical fibred communication (1.3 and 1.55μm wave length) is same InP/InGaAs system.

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2 Principle of operation[2]

As shown in Fig. 1, the photo-controlled MOBILE′s is formed by two RTD connected in series. The upper is load RTD while the lower is drive RTD that is connected with a HPT in parallel. The emitter of drive RTD is connected with ground and the collector of the load RTD is connected to a clock signal as another electric input. In

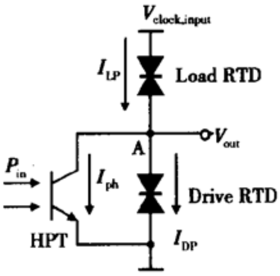

Fig. 1 Operating principle of photo-controlled MOBILE′s

Fig. 1, I_{LP}, I_{DP}, and I_{ph} are the peak currents flowing through the load RTD, the drive RTD, and photocurrent in HPT, respectively. When input light power P_{in} is zero, we can consider $I_{ph} \approx 0$. If we design the emitter area A_{El} of load RTD to be larger than that of the drive RTD A_{Ed} ($A_{El} > A_{Ed}$), $I_{LP} > I_{DP}$. From the analysis about the MOBILE′s, as $V_{clock} > 2V_{DP}$ (peak voltage of drive RTD), when the current on arriving at point A (I_{LP}) is larger than the current on departing A (I_{DP}), the output voltage V_{out} will go to a high level. When the input light power P_{in} increases to a critical value P_{inc}, this critical P_{inc} produces a critical photocurrent I_{phc} in HPT. To adjust A_{El} and A_{Ed}, let $I_{LP} - I_{DP} = I_{phc}$. As $P_{in} > P_{inc}$, then $I_{ph} > I_{phc}$, $I_{LP} - I_{DP} < I_{phc}$, $I_{ph} + I_{DP} > I_{LP}$. For this case, the current on arriving at point A (I_{LP}) is smaller than the current on departing A ($I_{ph} + I_{DP}$). So the output voltage V_{out} will go to a low level. As $V_{clock} < 2V_{DP}$, V_{out} always maintains a low level. These results of logic function are the same as the conventional electrical MOBILE′s besides the input light power P_{in}.

3 Simulating experiment

In order to verify above proposition about the photo-controlled MOBILE′s, the simulating experiment is taken. In our simulating experiment, HPT is replaced with a silicon phototransistor 3DU32. Two RTDs used in the experiment are fabricated. The experimental circuit is shown in Fig. 2. In Fig. 2(a) or (b), the left is LD driving circuit. The LD is driven by the collector current of silicon bipolar transistor 3DG6. The P_{in} is controlled by E-B voltage (V_{BE}) of a bipolar transistor 3DG6. The right is the circuit of MOBILE′s with a phototransistor as an input terminal. The simulating experiment can

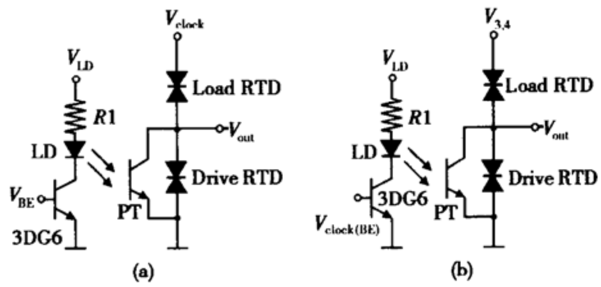

Fig. 2 Simulating experimental circuit (a) Constant light power; (b) Constant load RTD bias V_3 or V_4

be divided in two steps. (1) In Fig. 2(a), V_{BE} is fixed at a constant voltage 1.15V or 0V and V_{LD} = 6.07V. The corresponding I_{LD} are 33mA and 0. The voltage at the collector of load RTD uses a clock pulse. The amplitude of clock pulse is V_{clock} = 0.2~ 1.77V, and the frequency of clock pulse is f_{clock} = 12.3kHz. The experimental results are shown in the wave diagram of Fig. 3. The upper curve shows V_{clock} and the lower curve shows V_{out}. Figure 3(a) corresponds the V_{out} for V_{BE} = 0. Figure 3(b) corresponds the V_{out} for the V_{BE} = 1.15V. From Fig. 3, we can see that for V_{BE} = 0 or $P_{in} \approx 0$. As amplitude of V_{clock} = 1.77V (> $2V_{P'}$, for this case, $V_P \approx 0.7$V), V_{out} is in a high level (Fig. 3(a)), and for V_{BE} = 1.15V or $P_{in} > P_{inc}$, then $I_{ph} > I_{phc}$. As V_{clock} = 1.77V, V_{out} is in a lower level (Fig. 3(b)). (2) In Fig. 2(b), the bias voltage of load RTD is fixed at V_3 = 1.7V (> $2V_P$), or V_4 = 0V (<

$2V_P$). At the base of bipolar transistor 3DG6, we use the pulse voltage V_{clock} to drive laser diode. Amplitude of V_{clock} equals 0.47~ 2.05V, frequency of clock pulse is f_{clock}= 12.3kHz, V_{LD}= 4.8V. The average I_{LD} = 20mA. The experimental results are shown in Fig. 4. The upper curve shows V_{clock}(connected on base terminal of 3DG6). The lower curve shows V_{out}. Figure 4(a) corresponds the V_{out} for V_{bias}= V_3= 1.7V (> $2V_p$), while Figure 4(b) corresponds the V_{out} for V_{bias}= V_4= 0V. From Fig. 4(a), we can see that for V_3= 1.7V (> $2V_p$, V_p= 0.7V), when $V_{clock(BE)}$ = 2.05V, P_{in}> P_{inc}, I_{ph}> I_{phc}. I_{ph}+ I_{phc} > I_{LP}, V_{out} is in the lower level, when $V_{clock(BE)}$ = 0.47V, P_{in}< P_{inc}, I_{ph}< I_{phc}, I_{ph}+ I_{phc}< I_{LP}, V_{out} is in the high level. So the wave shape is opposite between upper and lower curves. In Fig. 4(b), the V_{bias}= V_4= 0V (< $2V_p$, V_p= 0.7V). So, the V_{out} always is in lower level. All of the experimental results show the logic function as the same as that we have analyzed in the paragraph of principle of operation. It is demonstrated that the photo-controlled MOBILE's have the same logic function besides using an optical input power P_{in} replacing an electrical input signal.

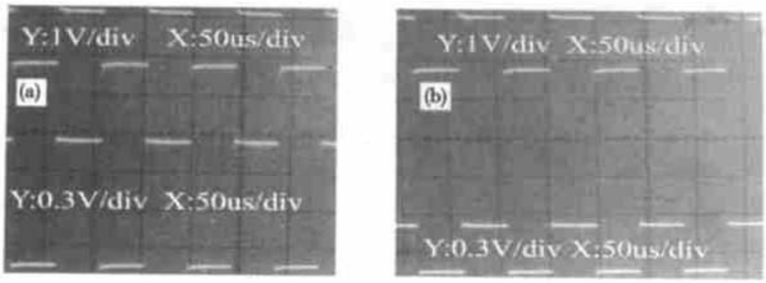

Fig. 3 Wave diagram for two constant P_{in}(controlled by V_{BE})

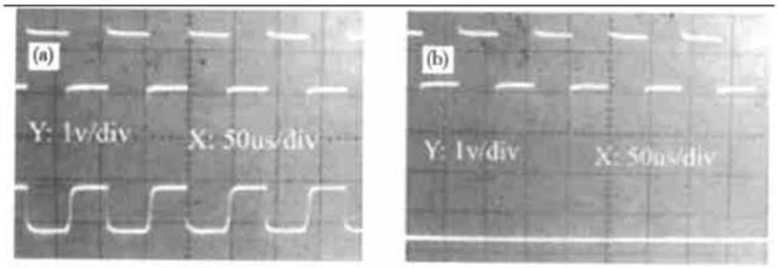

Fig. 4 Wave diagram for two bias voltage of load RTD (V_3= 1.7V, V_4= 0V)

4 Experiment of double input photo-MOBILE's

As shown in Fig. 5, the double input photo-MOBILE's is formed by two RTDs connected in series, and two HPTs connected in parallel with each RTD. If we design the parameters of two RTDs and two HPTs to be the same, the load RTD with load HPT and drive RTD with drive HPT are symmetric each other. Now, let the input light power P_{in} radiate only one of both HPT_L and HPT 2. For example, at first, P_{in} radiates HPT_D only, (HPT_L is in dark), then I_{DP}+ I_{HPT_D}> I_{LP}, V_{out} will be in lower level. Secondly, P_{in} radiates HPT_L only (HPT_D is in dark), then I_{DP}+ I_{HPT_L}> I_{LP}, V_{out} will be in high level. So, for a same P_{in}, the V_{out} will change its electrical levels as the radiated HPT varies. If let P_{in} radiate two HPT at the same time, the V_{out} will be in an instable state.

The simulating experiment of double input photo-MOBILE's has been carried out. In this experiment, HPT is replaced by silicon phototransistor 3DU32. The input light power corresponds 2300lx. As a light of 2300lx radiates on HPT_L and

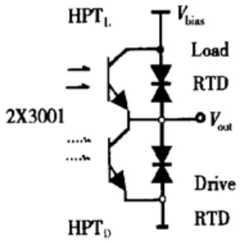

Fig. 5 Circuit of double input photo-MOBILE's

HPT$_D$, respectively, the V_{out}-V_{bias} characteristic of double input photo-MOBILE's has been measured shown in Fig. 6. The V_{bias} is provided by a DC power supply in which the output voltage can be adjusted continuously. Figure 6 shows that during the range of V_{bias} from 1.1V to 1.9V, as a light of 2300lx radiates at HPT$_L$, then suddenly changes to radiate at HPT$_D$ or the change is on a opposite direction, the variation in V_{out}. ΔV_{out} will be in a range of 0.85~1.4V. This value of ΔV_{out}, in general, is satisfied the demand of common logic operation in circuit.

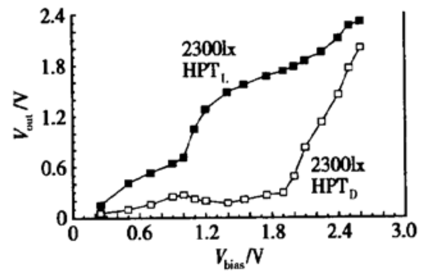

Fig. 6 V_{out}-V_{bias} characteristic of double input photo-MOBLE's

5 Circuit simulation

As shown in Fig. 7, the photo-MOBILE can be expressed by an equivalent circuit of a phototransistor connected with a driver RTD in parallel.

For the device model of RTD, we adopt the physics-based RTD current-voltage equation[4].

$$J = J_{RT} + J_{ex}$$

$$J_{RT} = A\ln\left[\frac{1+e^{(B-C+n_1V)q/kT}}{1+e^{(B-C-n_1V)q/kT}}\right] \times \left[\frac{\pi}{2}+\tan^{-1}\left(\frac{C-n_1V}{D}\right)\right]$$

$$J_{ex} = H\left(e^{n_2qV/kT}-1\right)$$

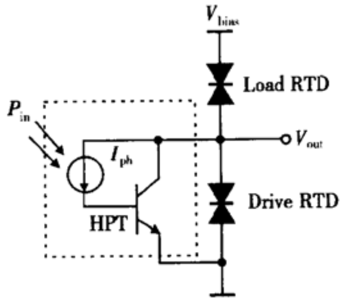

Fig. 7 Equivalent circuit diagram for photo-controlled MOBILE

The simulated results agree well with the experiments we obtained before[5].

For the device model of HPT, a large signal standard bipolar SPICE model based on Gummel-Poon model is employed to simulate common emitter characteristics of HPT. The photocurrent is modeled as a current source I_{ph} connected between the base and collector terminals. We take above both device models on RTD and HPT into the PSPICE program based on equivalent circuit of photo-MOBILE shown in Fig. 7. The simulated results are shown in Fig. 8. In which, the top diagram represents the bias voltage at the collector of load RTD in a clock pulse form. In this case, 2V is assumed larger than $2V_{DP}$, and 1V is smaller than $2V_{DP}$. The middle diagram represents input optical power P_{in}. In this case, 6μW is assumed large than P_{inc}. The lower diagram represents the output voltage V_{out}. From Fig. 8, it is clear that as V_{bias} is smaller than $2V_{DP}$, the V_{out} is always in a lower level. As V_{bias} just is larger than $2V_{DP}$, the V_{out} is oppo-

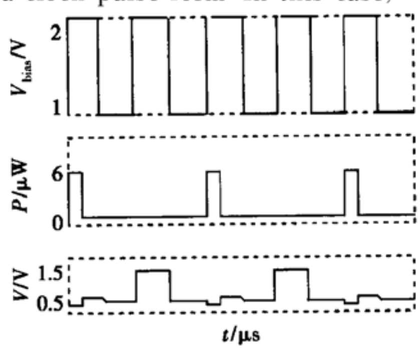

Fig. 8 Wave form of simulated results on photo-MOBILE

site with input light power P_{in}, V_{out} is in a high level as $P_{in} < P_{inc}$, and V_{out} is in a lower level as $P_{in} > P_{inc}$. These results agree well with the analysis from the paragraph of operating principle and the results from simulating experiments.

6 Conclusion

In this paper, a photo-controlled MOBILE´s of photo-MOBILE´s with RTD/HPT structure has been proposed and demonstrated by simulating experiments and circuit simulation. The results of simulating experiment show that the photo-MOBILE´s have the same logic functions besides it´s input light signal. In addition, the experiment on the double input photo-MOBILE´s demonstrates that these photo-controlled logic elements have the advantages of multiple functions, flexible in application, and easily incorporating with optical communication.

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光控单稳-双稳转换逻辑单元*

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摘要: 用光电晶体管替换 HEMT 作为输入端, 结合 RTD 可以构成新的光控逻辑单元, 它具有光电流开关和自锁功能, 该功能在实验及电路模拟中得到证实. 在此基础上, 若以异质结光电管(HPT)和 RTD 集成, 可以设计和制作诸如 D 型触发器等不同功能的光控逻辑电路单元.

关键词: 单-双稳态转换的逻辑电路单元; 光控; 模拟

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