Monolithically Fabricated OEICs Using RTD and MSM *

Hu Yanlong†, Liang Huilai, Li Yihuan, Zhang Shilin, Mao Luhong, and Guo Weilian

(School of Electronic Information Engineering, Tianjin University, Tianjin 300072, China)

Abstract: Two kinds of monolithically fabricated circuits are demonstrated in GaAs-based material systems using resonant tunneling diodes (RTD) and metal-semiconductor-metal photo detectors (MSM PD). The electronic characteristics of these fabricated RTD devices, MSM devices, and integrated circuits are tested at room temperature. The results show that the current peak-to-valley ratio is 4, and the photocurrent at 5V is enhanced by a factor of nearly 9, from 2 to about 18μA by use of recessed electrodes. The working theory and logical functions of the circuits are validated.

Key words: resonant tunneling diode; metal-semiconductor-metal photo detector; device simulation; monolithic optoelectronic integration

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1 Introduction

Functional devices based on resonant tunneling diodes (RTD) are emerging as promising candidates for use in integrated circuits due to their unique negative differential resistance (NDR), structural simplicity, relative ease of fabrication, inherent high speed, design flexibility, and versatile circuit functionality[1]. Double-barrier RTDs are based on the resonance of electron wave functions in quantum wells. Metal-semiconductor-metal (MSM) photodetectors are popular in modern optical communication systems. They have several advantages over traditional p-i-n photodiodes. First, they have a planar structure, which is compatible with most semiconductor devices, making them ideal for optoelectronic integrated circuit (OEIC) applications. Second, because of their geometry, they have a lower capacitance for the same active area, resulting in a lower RC time delay. Third, the fabrication process for the devices is very simple and compatible with regular IC processes. The operation speed of transistor-based OEICs has reached 100Gbit/s[2], so they will be indispensable in future optical communications.

2 Circuit design and experiment

As shown in Fig. 1, two kinds of monolithic opto-controlled negative difference solid circuits are fabricated. One is an opto-controlled switch, composed of an RTD driver serially connected to an MSM loader. The other consists of two RTDs (the

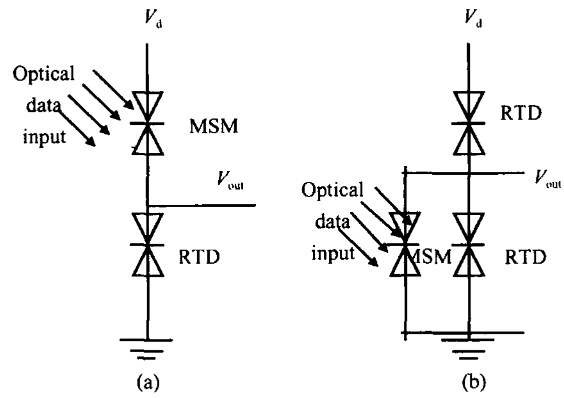

Fig. 1 Circuit diagram of monolithic opto-controlled negative difference solid circuits

lower is the driver, and the upper is the loader) and one MSM. A circuit consisting of an RTD pair and a current modulator is known as a monostable-bistable transition logic element (MOBILE). To real-

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† Corresponding author. Email: tianwaitian12@eyou.com

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ize an optical interface, we employ the MSM as the current modulator. The MSM is connected in parallel to the driver RTD in order to obtain a sufficient logic swing.

Firstly, we analyze the operation principle of the circuits. In Fig. 1(a), if the MSM is un-illuminated, there will be no current through the circuit (Fig. 2(a)); if the MSM is illuminated, the switch is closed (the output is high, as shown in Fig. 2(b)). In Fig. 1(b), the operation mode of this circuit is determined by whether a light beam is applied to the MSM and by the value of V_d. When V_d is low, there will be only one stable point (low output). If illuminated (Fig. 2(d)), the output voltage will be much lower than when there is no light (Fig. 2(c)). When V_d is high, there will be two stable points. Which stable point will be selected is determined by the relationship between the magnitude of the peak current of the driver RTD (I_{DP}) and that of the load RTD (I_{LP}). Here, the photocurrent through the MSM (I_{MSM}) effectively controls the relationship between I_{DP} and I_{LP}. If un-illuminated and if $I_{DP} < I_{LP}$ (illuminated and $I_{DP} + I_{MSM} > I_{LP}$), the stable point becomes S2(S1) of the high-(low-) voltage output, as shown in Fig. 2(e) (Fig. 2(f)). In our design, the mat-ching of the currents of the driver RTD, the loader RTD, and the MSM is very important. To make $I_{DP} < I_{LP}$, the driver RTD's electrode ($6\mu m \times 5\mu m$) is designed to be much smaller than the loader RTD's ($6\mu m \times 6\mu m$). To make $I_{DP} + I_{MSM} > I_{LP}$, the MSM's current must be large enough, and recessed electrodes are introduced.

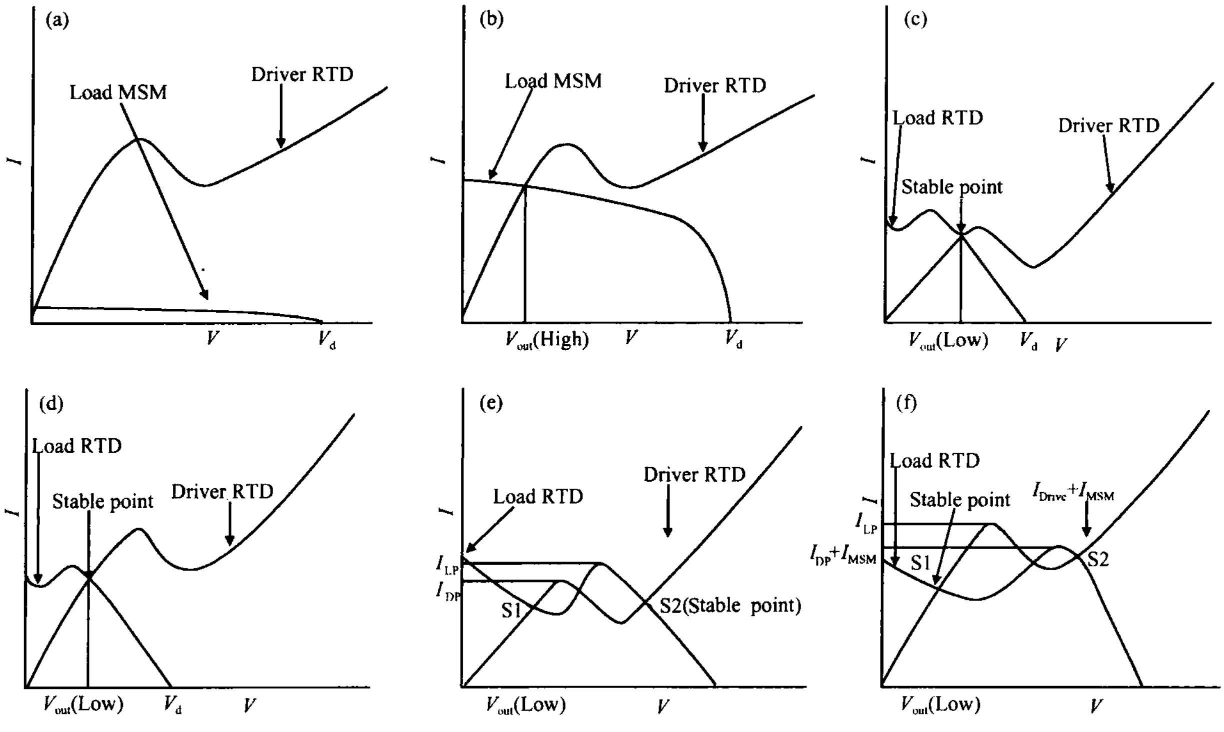

Fig. 2 Operation principle of OEIC (a) Un-illuminated (switch); (b) Illuminated (switch); (c) Un-illuminated and low-level clock (inverter); (d) Illuminated and low-level clock (inverter); (e) Un-illuminated and high-level clock (inverter); (f) Illuminated and high-level clock (inverter)

The RTD was grown by molecular beam epitaxy (MBE) on semi-insulating GaAs substrate. It is nominally a 7-layer device (n^+ GaAs/i-GaAs/AlAs/$In_{0.15}Ga_{0.85}As$/AlAs/i-GaAs/n^+-GaAs). The quantum well structure is an AlAs/$In_{0.15}Ga_{0.85}As$/AlAs barrier/well/barrier structure, and the heavily doped n^+ GaAs layers are designed for the formation of the emission or the collector electrodes thereon. The undoped i-GaAs layer guards the quantum well against undesired out-diffusions of impurities from n^+-GaAs layers.

The integration process began with the fabrication of the emission electrode of the RTD. Au-Ge-Ni was used for the emission metallization. A

50～100nm of Au-Ge-Ni was sputtered, and a 100～200nm of Au was formed as the interconnect metal. Next, mesas were etched down to the n+-GaAs buffer layer, and the Au-Ge-Ni collector electrodes of the RTD were made with the same method as for the emission electrode. Bigger mesas were formed through etching the n^+-GaAs buffer layer down to the semi-insulator substrate, and the Ti-Au finger electrodes were then formed thereon. The etchant in the experiment was a solution of H_2SO_4 : H_2O_2 : H_2O with relative volumes of 1 : 8 : 80. At room temperature, the etching rate was about 7～10nm/s. In order to increase the area exposed to the light, the growth substrate was removed to enhance responsivity, and the interdigitated finger electrodes were sputtered on the bottom of the device. The ohmic contacts of the MSM electrode were formed by sputtering a Ti/Au sandwich through a liftoff process. The Schottky barrier metal (Ti) was very thin, about 50nm. The 200nm of gold served as a low-resis-tance interconnect. The electrodes of the MSMs were interdigitated (these are called fingers). They were alternately biased to create a relatively high electric field between fingers. The distance between two fingers is the active semiconductor region, called the finger gap. Photons strike the semiconductor material between the fingers and create electron-hole pairs, whose flow creates a current. In the experiment, the finger gap was 5μm, and the finger width was 3μm.

3　Results and discussion

Room-temperature current-voltage curves of both types of photodetectors are shown in Fig. 3. At a bias voltage of 5V, the photodetector with recessed electrodes clearly exhibits a larger photocurrent than the conventional photodetector. At 5V the photocurrent is enhanced by a factor of nearly 9, from 2 to about 18μA. We have consi-dered possible mechanisms behind the enhanced responsivity. The main difference between these two types of photodetectors is whether the substrate is removed before sputtering. Removing the substrate can eliminate finger shadowing to enhance responsivity. Furthermore, the recessed cathode results in more effective collection of the speed-limiting holes due to both a strengthened electric field and a shortened transit path around the absorption region[3,4].

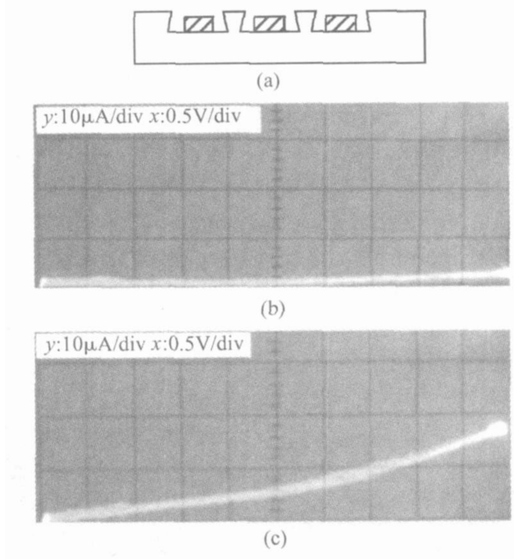

Fig. 3　(a) Schematic cross-section of MSM; (b) I-V curves of MSM without the swallow trench; (c) I-V curves of MSM with the recessed electrodes

In order to simulate the performance of the RTD, large-signal simulations with PSPICE 9.2 were performed. The simulation result is shown in Fig. 4 (a). The measured current-voltage curve of the RTD by an XJ4810 semiconductor characterization system at room temperature is shown in Fig. 4 (b). The peak current I_p is 40μA, the valley current is 10μA, the peak voltage V_p is 1.5V, and the peak-to-valley current ratio is 4.

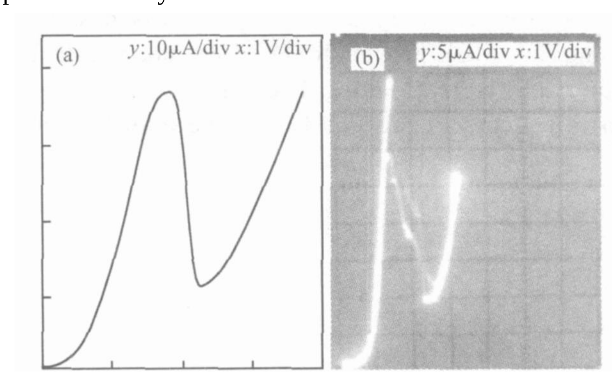

Fig. 4　(a) Simulated I-V curve of the RTD by PSPICE; (b) Measured I-V curve of the RTD

The logic functions of the OEICs were measured on-chip with XJ4241 and COS6100 oscilloscopes respectively, and the results are shown in Fig. 5. When a light beam is incident on the MSM, the output is high; there is no current through the circuit and the output is low (Fig. 5(a)) when no light beam exists. The switch function is realized. As to the opto-controlled inverter circuit (Fig. 5(b)), when V_d is low, the output is low. If a light beam is incident on the MSM, the output voltage is much lower than that when there is no light. When V_d is high and no light beam is supplied, the output is high. If light is supplied, the logic output undergoes a transition from high to low by exceeding the peak current point of the loader RTD. In summary, when light is supplied, the output current is lower than that when there is no light. Thus the function as an inverter is realized[5].

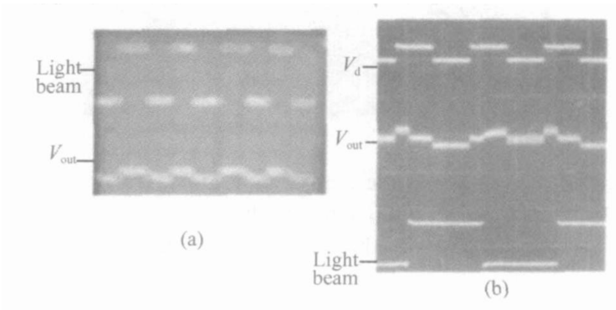

Fig. 5 Input and output waveforms of optoelectric integrated circuit (a) Opto-controlled switch; (b) Opto-controlled inverter

4 Conclusion

Two kinds of monolithic opto-controlled negative difference solid circuits using RTDs and MSMs are presented. The IC was newly designed using an MBE-grown RTD/MSM stacked-layer epitaxial heterostructure. The RTDs yield a peak-to-valley current ratio of 4, and the interdigitated MSMs with the growth substrate removed demonstrate a high current of 18μA at a bias voltage of 5V at room temperature. By analyzing the operation principle of the circuits and the test results, the operation theory and logical function of the circuits are validated. There are several kinds of photo-detectors integrated with RTDs[6], but monolithically fabricated OEICs using RTD and MSM photo-detectors have only been reported by Liang *et al*.[7].

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GaAs 基 RTD 与 MSM 光电集成 *

胡艳龙† 梁惠来 李益欢 张世林 毛陆虹 郭维廉

(天津大学电子信息工程学院，天津 300072)

摘要：报道了 GaAs 基共振隧穿二极管(RTD)与金属-半导体-金属光电探测器(MSM PD)单片集成的两种光电集成电路，并在室温条件下分别测试了 RTD 器件、MSM 器件和集成电路的电学特性. 测试表明：RTD 器件的峰谷电流比为 4；由于改进了在半绝缘 GaAs 衬底上制作 MSM 的方法，5V 偏压下的电流由原来的 2μA 增加到了 18μA，基本实现了两种电路的逻辑功能.

关键词：共振隧穿二极管；金属-半导体-金属光电探测器；器件模拟；单片光电集成
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† 通信作者. Email：tianwaitian12@eyou.com
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