Extended Abstracts of the 1999 International Conference on Solid State Devices and Materials, Tokyo, 1999, pp. 242–243 **D-6-1**

Invited

Ultrahigh-speed and Low Power Integrated Circuits Employing Resonant Tunneling Diodes

Koichi Maezawa

School of Engineering, Nagoya University,
Furo-cho, Chikusa-ku, Nagoya-shi 464-8603, Japan
Phone:+81-52-789-5455 Fax:+81-52-789-5232 e-mail:maezawa@nuee.nagoya-u.ac.jp

1 Introduction

Recently, resonant tunneling diodes (RTDs) and resonant tunneling transistors (RTTs) have been attracting much attention as practical devices. This is due to their potential for high-speed operation as well as their ability to operate at room temperature. In addition to these features, one of the most significant features that makes the RTDs attractive is its functionality arising from negative differential resistance (NDR). Several functional devices using resonant tunneling phenomenon and their circuit applications have been proposed and demonstrated. Among them, we introduced a highly functional logic gate, called a MOBILE (MOnostable-BIstable transition Logic Element)[1], and demonstrated several circuit applications. In this paper, we will describe recent advances of the MOBILE ICs and related RTD applications.

2 Operating Principle of the MOBILE

The operating principle of the MOBILE is explained in Fig. 1[1]. It has two aspects: 1) employing the monostable-to-bistable transition of a circuit consisting of two NDR devices connected serially, and 2) driving this circuit by oscillating the bias voltage ($V_{\rm bias}$) to produce the transition. A stable point, S, in the $V_{\rm bias} < 2V_{\rm P}$ region splits into two branches, S1, S2, when $V_{\rm bias}$ increases through $2V_{\rm P}$. A small difference in the peak current between the two NDR devices determines the circuit's state after the transition. Therefore, the circuit forms a logic gate if the peak current of the NDR devices can be modulated according to input signals. The oscillatory varying bias voltage acts as a clock.

First, we used the junction gate resonant tunneling transistor which has p-type junction gates surrounding the RTD as a basic NDR devices[1, 2, 3]. Recently, this RTT was replaced by a parallel circuit of a resonant tunneling diode (RTD) and a HEMT[4]. This has several advantages. First, layer structure and the fabrication process can be optimized independently for RTDs and HEMTs. Second, co-integration of the MOBILE and the conventional circuit is possible. This enables us to design ICs using both the MOBILE and the conventional FET logic considering each merits and demerits.

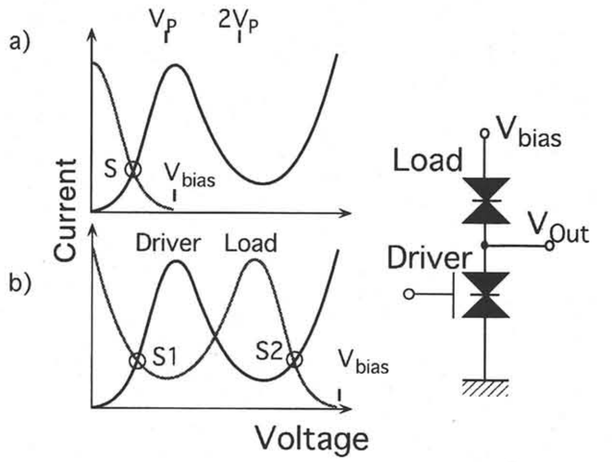

Fig. 1: Operating principle of the MOBILE. Load-curve diagrams for a) Monostable state, b) Bistable state.

The devices are fabricated using the InP-based RTD/HEMT integration technology[5]. Using these structure we can obtain good $I - V$ characteristics for both RTDs and HEMTs. The typical current density and the peak/valley current ratio of the RTD were $1 \times 10^5 \mathrm{A/cm}^2$ and 9, respectively.

3 Applications of MOBILEs

Several application circuits of the MOBILE have been reported. Figure 2 demonstrates the extremely high speed operation of the MOBILE[6]. This figure shows the input and output eye patterns at 35 Gb/s for the MOBILE inverter circuit. Though this is a simple circuit consisting of a MOBILE inverter and a DCFL-type output buffer, this circuit works as a D-FF with a return-to-zero mode output due to the latching operation of the MOBILE. (A non-return-to-zero mode D-FF using two MOBILEs and a resonant tunneling SR-FF has been also demonstrated at 12 Gb/s.[7]) The maximum operation speed of 35 Gb/s was close to the $f_{\rm T}$ of the HEMTs (gate length was $0.7\mu m$), and was still dominated by the speed of HEMTs. So, ultrahigh speed operation is expected using shorter gate HEMTs. The relatively small output ampli-

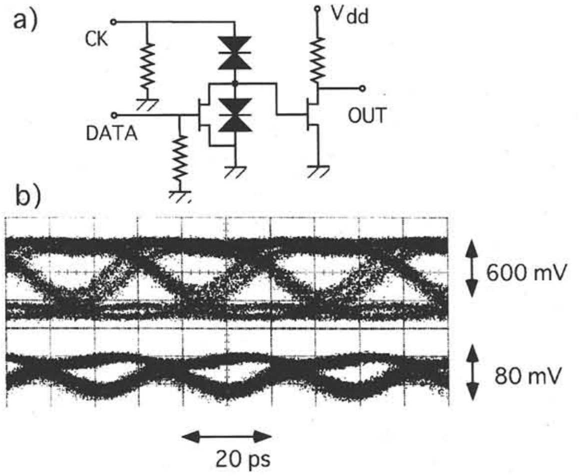

Fig. 2: Circuit configuration and operating eye pattern at 35 Gbps of the MOBILE Inverter.

tude of about 50 mV was due to the design of the output buffer circuit. The inner logic swing is estimated to be around 0.6 V. In fact, a practical output voltage level close to the widely used SCFL level has been obtained using SCFL type output buffer[8]. This indicates that the MOBILE has sufficiently large current drivability.

Moreover, we have fabricated a static frequency divider using MOBILEs[9]. The circuit consists of only two MOBILEs in a core circuit and can be operated at 34 GHz. The number of devices is reduced to be about 1/5 of that of the conventional frequency divider. This is extremely significant for obtaining high speed operation as well as low power consumption, since the wiring length should play a still more important role in determining the maximum operation speed for future ultrahigh speed ICs.

4 Extensions of MOBILEs

Several extensions of the MOBILE concept have been proposed recently. The MML (Monostable-Multistable transition Logic) extends the MOBILE to the multiple valued logic by increasing the number of the serially-connected RTDs[10]. Its operating principle was demonstrated by three and four valued logic gates. Moreover, 10 GHz operation of the multiple-valued quantizer for A-D converter has been successfully demonstrated using this principle[11]. One of the most interesting extensions is the optical input MOBILEs[12, 13], which convert an optical signal into an electrical one. The optical input MOBILE, where the input HEMT was replaced by the ultrahigh speed photo diode (UTCPD), have been demonstrated to demultiplex an 80 Gb/s optical signal into a 40 Gb/s electrical signal[12].

Though only digital applications were described here, analog applications are also promising. A lot of analog applications were proposed exploiting the strong non-linearity of the RTDs. Among these, chaos generator has been recently proposed as a novel application of RTDs[14]. Using the strong non-linearity of the RTDs It is possible to fabricate high frequency and controllable chaos generator suitable for MMICs. Although a chaos is often regarded as a random and incontrollable phenomenon, it is deterministic, and can be controllable in a limited time. Several applications using controlled chaos, such as a pulse pattern generator and a frequency divider, should be possible.

5 Summary

Recent progress of the resonant tunneling circuit technology was described. It was shown that the MOBILE technology consisting of RTD/HEMT integration is a promising candidate for the key component of the future ultrahigh-speed application.

References

[1] K. Maezawa, and T. Mizutani, Jpn. J. Appl. Phys., Vol. 32, p. L42, 1993.

[2] K. Maezawa, T. Akeyoshi, and T. Mizutani, IEEE Tran. Electron Devices, Vol. 41, p. 148, 1994.

[3] K. Maezawa, T. Akeyoshi, and T. Mizutani, IEEE Tran. Electron Devices, Vol. 42, p. 1005, 1995.

[4] K. J. Chen, K. Maezawa, and M. Yamamoto, IEEE Electron Device Lett., Vol. 17, p. 127, 1996.

[5] K. J. Chen, K. Maezawa, and M. Yamamoto, IEICE Trans. Electron., Vol. E-79-C, p. 1515, 1996.

[6] K. Maezawa, H. Matsuzaki, J. Osaka, M. Yamamoto, and T. Otsuji, IEEE Electron Device Lett., Vol. 19, p. 80, 1998.

[7] K. Maezawa, H. Matsuzaki, J. Osaka, M. Yamamoto, and T. Otsuji, Jpn. J. Appl. Phys., Vol. 37, p. L212, 1998.

[8] K. Maezawa, H. Matsuzaki, J. Osaka, H. Yokoyama, M. Yamamoto, and T. Otsuji, Jpn. J. Appl. Phys., Vol. 37, p. L1286, 1998.

[9] H. Matsuzaki, K. Arai, K. Maezawa, J. Osaka, M. Yamamoto, and T. Otsuji, Electron. Lett. Vol. 34, p. 70, 1998.

[10] T. Waho, K. J. Chen, and M. Yamamoto, IEEE J. Solid-State Circuits, Vol. 33, p. 268, 1998.

[11] T. Itoh, T. Waho, J. Osaka, H. Yokoyama, and M. Yamamoto, IEEE MTT-S Int. Microwave Symp., p. 197, 1998.

[12] T. Akeyoshi, N. Shimizu, J. Osaka, M. Yamamoto, T. Ishibashi, K. Sano, K. Murata, and E. Sano, Proc. Int. Conf. InP & Related Materials, Tsukuba, p. 423, 1998.

[13] Y. Ohno, S. Kishimoto, K. Maezawa, T. Mizutani, T. Akeyoshi, Jpn. J. Appl. Phys., Vol. 38, p. 2586, 1999.

[14] K. Maezawa, Y. Kawano, S. Kishimoto, and T. Mizutani, 11th Int. Conf. InP and Related Materials, Davos, p. 415, 1999.