Ultrahigh-Speed Circuits Using Resonant Tunneling Devices

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Abstract

Ultrahigh-speed circuit applications of resonant tunneling diodes (RTDs) have been developed. One of the key concepts is the merged utilization of RTDs and high electron mobility transistors (HEMTs). The integration technology for InP-based RTDs and HEMTs has been developed. Another key technology developed is a circuit configuration using series-connected RTDs, driven by a clocked bias, in combination with HEMTs. Given this circuit concept, various kinds of edge-triggered flip-flop circuits and multiple-valued quantizers featuring high-speed operation and compact configuration have been constructed. By extending this circuit concept, an optoelectronic circuit using RTDs and a photodiode has also been developed. High-speed operations have been demonstrated, including a delayed flip-flop circuit operating at 35 Gbit/s, multiple-valued quantizers operating at 10 GHz, a 2-bit analog-to-digital converter operating at 5 GHz and an optoelectronic circuit that demultiplexes an 80 Gbit/s optical signal into a 40 Gbit/s electrical signal. The presented results clearly show the potentiality of RTD-based circuits for the construction of unprecedented ultrahigh-speed communications and signal processing circuits.

1. Introduction

A resonant tunneling diode (RTD) features negative differential resistance (NDR) originating from resonant tunneling through a double-barrier heterostructure. The NDR provides the possibility of significantly reducing circuit complexity. The RTD also exhibits the fastest switching time (1.5 ps) [1] among any other semiconductor devices, which is due to its high-peak current density and relatively small capacitance. These distinct advantages have been the driving force for the research and development of quantum functional devices and circuits using RTDs [2]. Recently, an approach using RTDs in combination with advanced and well-matured conventional transistors has provided a practical way to construct ultrahigh-speed circuits that simultaneously feature low power consumption and reduced device count [3, 4]. In this paper we will review recent progress in ultrahigh-speed circuit applications of RTDs, focusing on key concepts and technologies.

One of the key concepts behind the recent progress is the merged utilization of InP-based RTDs and high electron mobility transistors (HEMTs) [5, 6]. In this approach, the RTDs are responsible for the switching function and data latching and the input-output isolation is provided by a conventional transistor used as an input-gate. From the point of view of circuit applications of RTDs, this approach also provides several advantages. First, room-temperature operation is ensured by using the RTD as an NDR device. Second, it allows the separate optimization of RTDs and conventional transistors. This separate optimization is advantageous for reproducibility and uniformity, which are indispensable for integration. Most importantly, this approach enables the use of RTDs only for the core of a circuit, leading to significant enhancement of the performance of various kinds of circuits.

Another key technology developed is a circuit configuration using series-connected RTDs, driven by a clocked bias, in combination with HEMTs. Given the generalized circuit concept of the modulation of the effective peak currents of RTDs through HEMTs connected in parallel to the RTDs, various kinds of edge-triggered flip-flop circuits and multiple-valued quantizers were newly developed. Owing to the edge-triggered and self-latching property of RTD-based circuits, these circuits feature compact circuit configuration. The circuits were fabricated using the RTD/HEMT integration technology, and high-speed operations have been experimentally demonstrated, including 35-Gbit/s operation of a delayed-flip-flop (D-FF) [7], 10-GHz operation of multiple-valued quantizers [3], and 5-GHz operation of a 2-bit flash-type analog-to-digital converter (ADC) using ternary quantizers as comparators [3].

This circuit concept was recently extended to construct an optoelectronic circuit using RTDs in combination with a photodiode. Demultiplexing an 80 Gbit/s optical input signal into a 40 Gbit/s electrical output signal was demonstrated for a fabricated optoelectronic circuit [8].

2. Monolithic Integration of InP-Based RTDs and HEMTs

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For the integration of RTDs and conventional transistors, InP-based RTDs and HEMTs have been used. This is because InP-based InGaAs/AlAs/InAs RTDs exhibit a high peak current density along with a good peak-to-valley current ratio and ultrahigh-speed switching characteristics at room temperature [1, 5], and because InP-based InAlAs/InGaAs HEMTs exhibit high transconductance and excellent high-frequency characteristics [9].

One of the key issues during the fabrication of RTD/HEMT integrated circuits is how to ensure the uniformity of the threshold voltages of the HEMTs. To combine InAlAs/InGaAs HEMTs with an InP etch-stop layer, for which MOCVD (metalorganic chemical vapor deposition) growth is suitable, and high-quality RTDs, for which MBE (molecular beam epitaxy) growth is suitable, a regrowth technique of RTDs by MBE on MOCVD grown devices was developed [10, 11] and applied for circuit fabrications. Figure 1 shows a schematic cross section of an RTD/HEMT integrated device, whose HEMT layer with an InP etch-stop layer was grown first by MOCVD and RTD layer was regrown by MBE on the HEMT layer. The characteristics of MBE-regrown RTDs, in spite of the growth interruption, are as good as those of conventional MBE-grown RTDs.

An InP-based RTD used for a series of circuit fabrications consisted of a 1.3 nm InGaAs/1.8 nm InAs/1.3 nm InGaAs strained well sandwiched by 1.6 nm AlAs barriers. Its peak current density (j_p) and peak-to-valley current ratio are 1. 1 x 10^5 A/cm^2 and10, respectively. Due to a well-controlled MBE technique, which is crucial for the growth of thin barriers and well, the standard deviation of the peak current of the RTDs having a j_p of 1.1 x 10^5 A/cm^2 and emitter area of 2 x 6 μm^2 showed an excellent value of 3 % over the 2-inch wafer [10].

3. Circuit Applications

3.1. High-Speed Flip-Flop Circuits

An edge-triggered flip-flop (FF) circuit, called the MOBILE (monostable-bistable transition logic element) has been the key to the recent development of ultrahigh-speed circuit applications of RTDs. The MOBILE's core consists of two RTDs connected in series and a HEMT as shown in Fig. 2(a) [12-14]. The HEMT is used as an input gate and modulates the effective peak current of the RTD. The output of "high" or "low" is obtained at the rising edge of the clocked bias according to the input applied to the HEMT. The output is maintained while the clocked bias is high as shown in Fig. 2(b). This simple MOBILE FF works as a D-FF with a return-to-zero mode output. By using the MOBILE as a circuit component, various FF circuits can be designed. These circuits have been fabricated using the InP-based RTD/HEMT integration technology, and high-speed circuit operations have been confirmed, including 35 Gbit/s operation of a D-FF [7] as shown in Fig. 2 (c) and 34 GHz operation of a static binary frequency divider [15]. Most significantly, these operating speeds are comparable to the current gain cutoff-frequency (f_T) of the 0.7 μm-gate-length HEMTs used in the circuits.

The circuits also feature low power consumption. For example, the estimated power consumption in the core circuit of the MOBILE FF is less than 2 mW. This is due to (1) the simple configuration, (2) the small dynamic power dissipation resulting from the small RTD capacitance of around 2 fF/μm^2 [1], and (3) the operating current level being lowered to the small valley current level at the steady state while the clock is high.

By extending the circuit concept of the MOBILE to include three or more RTDs connected in series, a variety of functional circuits of reduced complexity can be constructed [16-18]. These include a literal gate, multiple-valued quantizers, and a programmable logic gate performing NAND, NOR, AND, OR, and XOR according to the appropriately applied control voltages. The principal of operation behind a generalized circuit is to control the switching sequence of these RTDs at the rising edge of the clocked bias through the modulation of the peak currents of RTDs by input signal applied to the HEMT connected in parallel to them. The switching sequence obeys the simple rule that the RTD with the smallest peak current switches from the peak (low voltage state) to the valley (high voltage state) first.

Figure 3(a) shows the circuit configuration of the fabricated ternary quantizer [3]. The core circuit consists of four RTDs connected in series and two HEMTs, one for the input gate and the other for the clock driver. Through the effective peak current modulation of RTDs X and Y by HEMT Q1, the circuit has two threshold voltages as shown in Fig. 3(b). The circuits were fabricated using the InP-based RTD/HEMT integration technology, and a three-level output was clearly obtained at the clock of 10 GHz and input of 1 GHz as shown in Fig. 3(c).

The presented RTD-based circuits will be useful in a number of systems requiring unprecedented ultrahigh-speed operation capability. Due to the rapid growth of various multimedia services, the demand for large-capacity communication systems has continuously pushed the development of faster digital ICs as key devices for optical transmission networks. The presented RTD/HEMT FF circuits are promising for use in future-generation ultrahigh-speed digital ICs. An ultrafast analog-to-digital converter (ADC) will be a key device for future wireless communications in which analog-to-digital conversion as close to the antenna as possible is anticipated. RTD-based circuits are highly suitable for the implementation of ultrafast and compact comparators of flash-type ADCs.

3.2. Analog-to-Digital Converters

Extensive work is currently being carried out to construct ultrahigh-speed ADCs using RTDs and HEMTs. Broekaert et al. developed a flash-type ADC using binary quantizers consisting of RTDs and HEMTs as comparators and demonstrated 2-GHz operation of a 4-bit ADC [4]. Waho et al. proposed the use of multiple-valued quantizers consisting of RTDs and HEMTs as comparators, which enabled the reduction of the number of comparators, and predicted 10-GHz clock frequency operation for a 4-bit ADC [19]. Itoh et al. recently demonstrated high-speed operation, at up to 5-GHz clock frequency, of a 2-bit ADC in which comparators were implemented with ternary quantizers [3]. Fig. 4(a) shows the block diagram of a fabricated 2-bit ADC. The ternary quantizers are followed by encoding circuits. Return-to-zero mode 2-bit Gray code output was successfully obtained for a clock signal of 5 GHz and input signal of 400 MHz as shown in Fig. 4(b).

3.3. Optoelectronic Circuits Using RTDs and a Photodiode

Beyond the 100 GHz region, the bandwidth limitation of electrical input to a chip will be a serious obstacle and will inevitably require the optical signal input to a chip. A compact circuit configuration will also be crucial for reducing the interconnection delay in a chip. To meet these requirements, the circuit concept of the MOBILE consisting of two RTDs and a HEMT has recently been extended to construct an optoelectronic logic circuit consisting of two RTDs and a photodiode [Fig. 5(a)] [8]. An InP-based photodiode called the uni-traveling-carrier photodiode (UTC-PD), which features both a wide bandwidth and high-saturation output power, was monolithically integrated with InP-based RTDs [Fig. 5(b)] [20]. The fabricated circuit demultiplexed an 80 Gbit/s optical signal into a 40 Gbit/s electrical signal [Fig. 5(c)] at a small power consumption of 8 mW [8]. The developed RTD/UTC-PD circuit is highly attractive as a key device for over-100-GHz digital circuits due to its optical input capability, compact circuit configuration, and inherent ultrahigh-speed operation.

4. Conclusion

Recent progress in ultrahigh-speed circuit applications of RTDs has been summarized. One of the key concepts is the merged utilization of RTDs and HEMTs, or the use of RTDs in combination with a photodiode. Another key technology is a circuit configuration using series-connected RTDs and HEMTs connected in parallel to the RTDs. These technologies provide a highly practical means of constructing ultrahigh-speed circuits. Various high-speed circuits, including a 35-Gbit/s D-FF, 10-GHz multiple-valued quantizers, a 5-GHz 2-bit ADC, and an optoelectronic circuit that demultiplexes an 80 Gbit/s optical input signal into a 40 Gbit/s electrical signal, have been demonstrated. All these recent accomplishments clearly show that the use of RTDs in combination with the most advanced conventional transistors or photodiodes is promising for constructing future-generation ultrahigh-speed digital and mixed-signal circuits.

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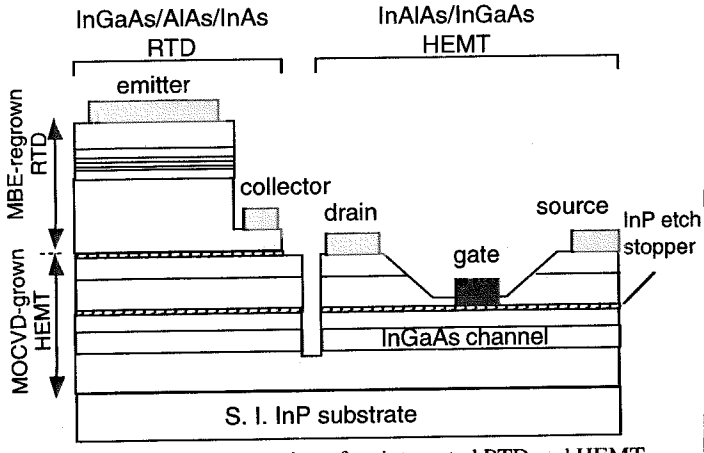


Fig. 1. Schematic cross section of an integrated RTD and HEMT. The RTD consists of an InGaAs/InAs/InGaAs well sandwiched by AlAs barriers.

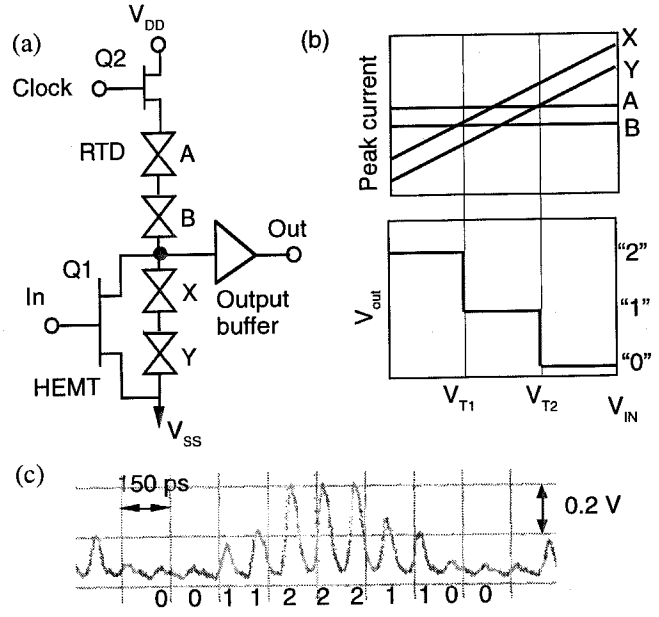


Fig. 3. Ternary quantizer. (a) Circuit configuration. (b) Peak currents as a function of input voltage and transfer charactreistics. (c) Output waveform (clock: 10 GHz, input: 1 GHz).

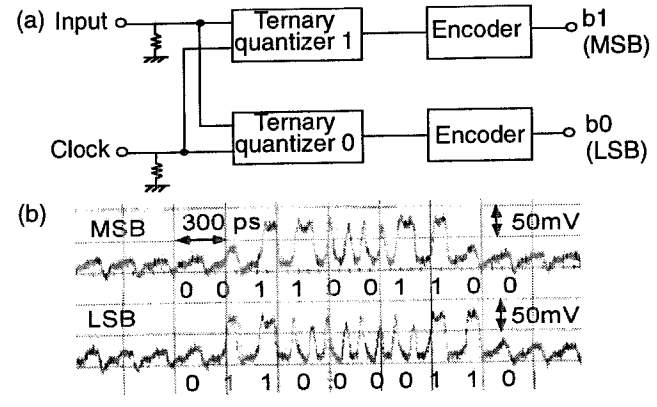


Fig. 4. Fabricated 2-bit ADC. (a) Block diagram. (b) Output waveforms (clock: 5 GHz, input: 400 MHz).

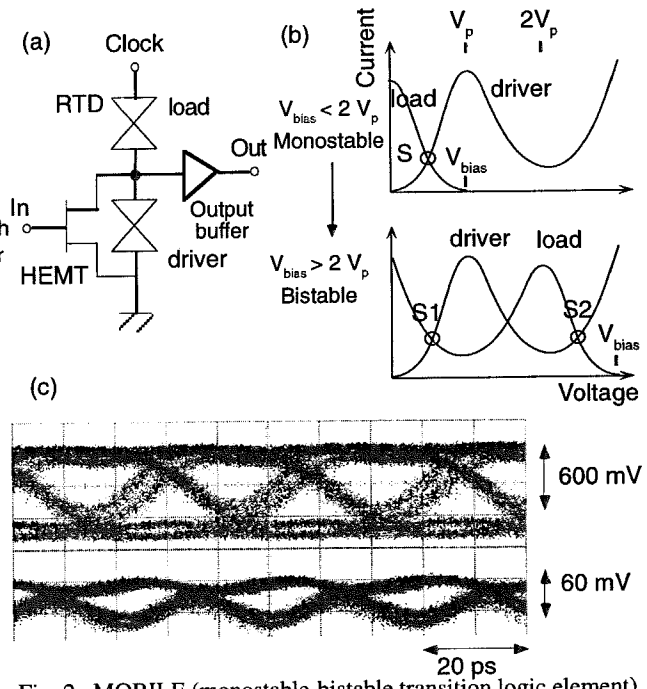
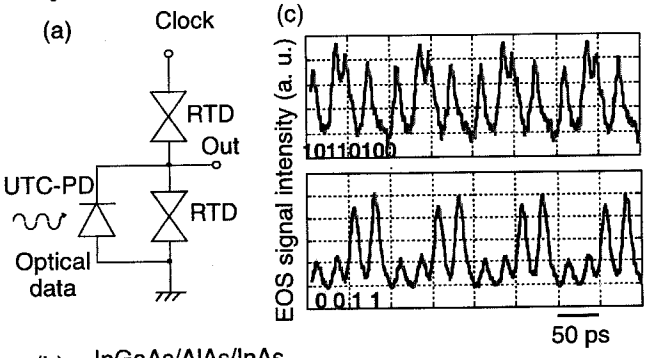


Fig. 2. MOBILE (monostable-bistable transition logic element) flip-flop using RTDs and a HEMT. (a) Circuit configuration of the fabricated circuit. (b) Load line curves showing the monostable-to-bistable transition. (c) Input (upper trace) and output (lower trace) eye patterns at 35 Gbit/s.



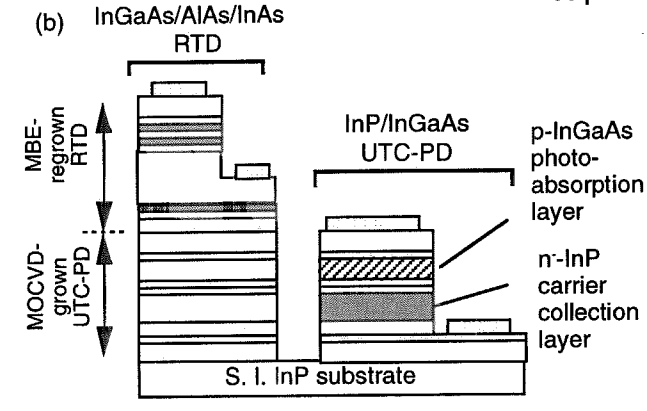


Fig. 5. Optoelectronic circuit using RTDs and a uni-traveling-carrier photodiode (UTC-PD). (a) Circuit configuration. (b) Schematic cross section of an integrated RTD and UTC-PD. (c) Waveforms of electro-optic sampling measurement; 80 Gbit/s optical input data (upper trace) and inverted 40 Gbit/s demultiplexed electrical output data (lower trace).