1.7-ps, Microwave, Integrated-Circuit-Compatible InAs/AlSb Resonant Tunneling Diodes

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***Abstract*—Microwave integrated-circuit-compatible InAs/AlSb resonant tunneling diodes (RTD's) have been fabricated. The resulting devices have peak current densities of 3.3×10^5 A/cm^2 with peak-to-valley ratios (PVR's) of 3.3. Switching transition times of 1.7 ps are measured using electro-optic sampling techniques.**

IT IS widely believed that InAs- and InGaAs-based resonant tunneling diodes (RTD's) can be significantly faster than GaAs-based RTD's due to their substantially higher peak current densities [1], [2]. In this paper, we report the design and fabrication of microwave integrated-circuit-compatible InAs/AlSb RTD's. The devices have peak current densities of 3.3×10^5 A/cm^2 with peak-to-valley ratios (PVR's) of 3.3. Switching transition times of 1.7 ps are measured using electro-optic sampling techniques.

Peak current density is a crucial figure of merit for high-speed RTD switching applications [3]. Extremely high peak current densities (up to 4.5×10^5 A/cm^2) have already been demonstrated in InGaAs/AlAs/InAs RTD's [1], [4]. Similarly, InAs/AlSb RTD's have peak current densities as high as 5.0×10^5 A/cm^2 and have been used in hybrid microwave oscillators with operating frequencies up to 712 GHz [2], [5], [6]. Based on published current–voltage characteristics, the expected switching transition times of these high peak current density RTD's can be estimated to be around 1 ps [1], [7]. However, all of these peak current density RTD's have been fabricated using simple device processing technologies, which are not suitable for measuring the expected high-speed switching transitions.

The anticipated InGaAs/AlAs and InAs/AlSb RTD switching times represent a significant improvement over the best previously observed times of 6 ps in GaAs/AlAs RTD's [8], [9]. Although Whitaker *et al.* reported 2.0-ps measurements using GaAs/AlAs-based RTD's [10], those measurements remain controversial. As described by Brown *et al.* [7], those switching experiments were done under an overdrive condition, in which measured switching times do not represent the true switching time of the devices. In fact, the expected minimum switching time of these GaAs-based devices (with peak current densities of 4×10^4 A/cm^2) is around 12 ps [2].

We have developed a monolithic microwave-compatible fabrication process for InAs- and InGaAs-based high-speed RTD's to be used for high-speed applications. Proton isolation techniques are not effective for semiconductors like InGaAs and InAs, which have relatively small energy gaps. Therefore, a mesa-type processing technique must be used to achieve isolation. Fig. 1(a) and (b) shows the lateral and horizontal cross sections of a microwave-compatible RTD structure, respectively. The procedure used to fabricate the structure is as follows. Gold is evaporated to be used as the top ohmic metal and also as a mask to protect the mesa area. The quantum well and the upper conducting layers are etched away until the bottom conductive layer is reached, and a layer of Au is deposited to be used as the bottom ohmic metal. Then, using an isolation mask, we etch away all of the epilayers except the active areas. This is followed by an evaportion of Ti/Au interconnect metal, which forms coplanar waveguide (CPW) transmission lines on top of the semi-insulating GaAs substrate. A 2.5-μm-thick Au layer is used as an airbridge to connect the center of the CPW to the top ohmic metal of the RTD.

This fabrication process has been used to investigate InAs/AlSb RTD's. Devices were grown on 2-in-diameter semi-insulating GaAs substrates. Growth started with a 0.2-μm undoped InAs buffer layer, followed by a 0.8-μm-thick InAs with $n = 2.0 \times 10^{18}$ cm^{-3}. This layer was followed by a 500-Å-thick lightly doped ($n = 10^{17}$ cm^{-3}) InAs layer. The double-barrier region consisted of a 75-Å InAs quantum well sandwiched between two identical 18-Å (six monolayers) AlSb barriers. An undoped 100-Å InAs layer was grown after the double-barrier region. The structure was completed by a 0.2-μm n-type InAs contact layer doped to 2.0×10^{18} cm^{-3}.

Devices with active areas ranging from 4 μm^2 (2 × 2 μm) to 36 μm^2 (6 × 6 μm) are fabricated. Fig. 2 shows the I–V characteristics of a device we obtained from the

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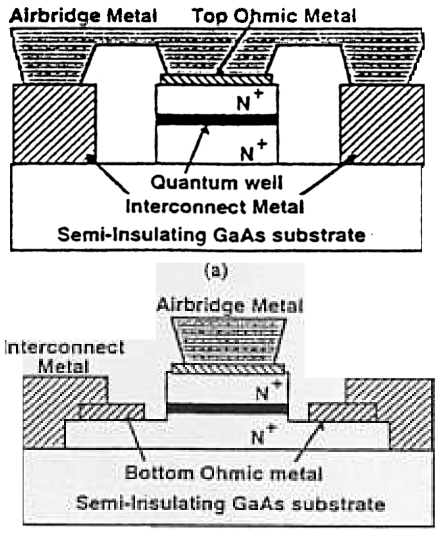

(a)

(b)

Fig. 1. (a) Lateral and (b) horizontal cross sections of the microwave integrated-circuit-compatible RTD structures.

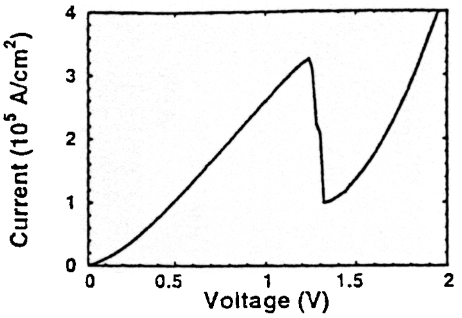

Fig. 2. Current–voltage characteristic of an InAs/AlSb RTD

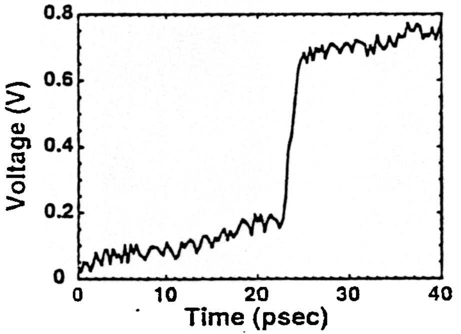

Fig. 3. 1.7-ps switching transition time is measured using electro-optic sampling techniques.

preceding epitaxial design and fabrication process. The device has a peak current density of 3.3×10^5 A/cm^2 with a peak-to-valey ratio of 3.3. The expected switching time can be calculated by using the analysis explained in [3], which concludes that the minimum obtainable rise time in an RTD is approximately $5R_nC$, where R_n is the average negative resistance, i.e., the voltage difference between peak and valley points divided by the available current, and C is the device capacitance. From this analysis, the device has an estimated RC switching time of 1 ps. The switching time of this InAs/AlSb RTD is still limited by the RC time constant, as the full width at half maximum of the electron transmission coefficient for the device is 2.92 meV, giving an intrinsic response time of 200 fs.

In order to measure the switching times of these devices, we have used voltage step forming structures which consist of a 50-Ω coplanar transmission line with an RTD shunted to ground from the center conductor of the coplanar transmission line [8]. Switching was demonstrated by applying a dc bias and a sine wave to the transmission line. As the RTD switches, a step waveform begins to propagate along the transmission line. The resulting waveform can be measured by electro-optically sampling the voltage at a point just past the device [11]. The length of the transmission line was chosen to be long enough to allow measurement of the pulse rise time before any reflections return from the output pad. This allows us to see the actual switching of the device, independent of bond pad capacitance. Electronic probing techniques, by contrast, will be limited by the bond pad capacitance rather than by the device characteristics. Using a 4 × 4-μm device (with a total area of 16 μm^2), we have measured a 10–90% switching transition time of 1.7 ps with a voltage swing of 500 mV (Fig. 3). When the response of the electro-optic sampling system is deconvolved from this measurement, the typical switching transition time is found to be around 1.2 ps, which is very close to estimated switching times. This is a factor of 5 improvement over previous high-speed measurements using GaAs-based RTD's. To the best of our knowledge, this measurement is the fastest documented switching time for any semiconductor device. The measurement of these high-speed transitions shows the feasibility of the fabrication process for high-speed RTD integrated circuit applications.

In summary, we have designed and fabricated InAs/AlSb-based, microwave, integrated-circuit-compatible resonant tunneling diodes. The resulting devices had peak current densities of 3.3×10^5 A/cm^2. Switching transition times of 1.7 ps were measured using electro-optic sampling techniques.

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