Short Papers

Resonant Tunneling Diodes as Sources for Millimeter and Submillimeter Wavelengths

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Abstract—**High quality Resonant Tunneling Diodes have been fabricated and tested as sources for millimeter and submillimeter wavelengths. The devices have shown excellent I–V characteristics with peak-to-valley current ratios as high as 6:1 and current densities in the range of 50-150 kA/cm2 at 300 K. Used as local oscillators, the diodes are capable of state of the art output power delivered by AlGaAs-based tunneling devices. As harmonic multipliers, a frequency of 320 GHz has been achieved by quintupling the fundamental oscillation of a klystron source.**

I. Introduction

Resonant Tunneling Diodes (RTD's) exhibit very strong non linearity with short time response which make them attractive in non linear applications for millimeter and submillimeter wavelengths [1]. RTD's have already demonstrated their potential for a variety of high speed/high frequency applications [2]–[5]. In this paper we report on the effort of a group of laboratories in France on these novel devices with special emphasis on local oscillators and harmonic multipliers. The fabrication procedures in a whisker contacted technology and in a microwave compatible technology suitable for monolithic integration are outlined in Section II. The dc and ac characterizations are reported in Section III whereas the oscillator and multiplier results using the devices are described in Section IV.

II. Technological Process

The two types of epitaxial structures grown by molecular beam epitaxy are given in Fig. 1(a) and (b). Both samples noted A and B had 17 Å thick AeAs barriers and access regions with a stepped doping profile from $-1 - 2 \times 10^{17}\,cm^{-3}$ to $2 - 3 \times 10^{18}\,cm^{-3}$. They differ mainly owing to the strained $Ga_{0.9}In_{0.1}As$ layers so that structure B resembles a triple well resonant tunneling structure. The associated benefits are a reduction of the peak voltage and higher peak-to-valley current ratios (PVCR's) because the ground state can be lowered and the negative differential resistance effect involves the anti crossing of two confined states [6]–[8].

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GaAs	**2 $10^{18}cm^{-3}$**	**490 nm**
GaAs	**2 $10^{17}cm^{-3}$**	**50 nm**
GaAs	**undoped (UD)**	**5 nm**
AlAs	**UD**	**1.7 nm**
GaAs	**UD**	**4.5 nm**
AlAs	**UD**	**1.7 nm**
GaAs	**UD**	**5 nm**
GaAs	**2 $10^{17}cm^{-3}$**	**50 nm**
GaAs	**2 $10^{18}cm^{-3}$**	**500 nm**
	n^+ substrate	

(a)

GaAs	**3 $10^{18}cm^{-3}$**	**500 nm**
GaAs	**$10^{17}cm^{-3}$**	**10 nm**
GaAs	**undoped (UD)**	**5 nm**
$In_{.1}Ga_{.9}As$	**UD**	**5 nm**
GaAs	**UD**	**0.5 nm**
AlAs	**UD**	**1.7 nm**
GaAs	**UD**	**0.5 nm**
$In_{.1}Ga_{.9}As$	**UD**	**4 nm**
	Symmetrical layers	

(b)

Fig. 1. Growth sequence for the epilayer on n^+ substrate (sample A). (a) Sample B grown on semi-insulating substrate. (b)

The epilayers on n^+ substrate were processed using a whisker contacted technology including patterning of Ni/GeAu layers into matrix of 3.5 μm diameter dots on the epitaxial side of the wafer and uniform deposition on the back side followed by alloying of these layers to make ohmic contacts. Mesa isolation was performed by chlorine ion beam assisted etching, using the patterned metal as a mask. Some of the samples were thinned to a thickness of about 120 μm and polyimide was used to surround the diodes in order to aid whisker contact.

For the epilayers on S–I substrate, the diodes were fabricated in a microwave-compatible two-step mesa technology [9]. In that case, the devices were connected to low-loss transmission lines in such a way that they can be characterized at the wafer level. Such vertically integrated devices require a means of connecting the contact on the top of the mesa to the pad of the transmission line. We thus developed two versions: (i) a dielectric assisted cross-over and (ii) an air bridge interconnection. A scanning electron micrograph of a representative device is shown in Fig. 2. In this figure a coplanar probe configuration is apparent. Also clearly shown is the deposited strap which crosses over the mesa edges covered with Si_3N_4 layer appearing in dark. In the second version, the dielectric cross-over is replaced by an air bridge yielding a reduced parasitic capacitance.

III. DC and AC Characterization

Fig. 3(a) shows a typical current voltage I–V characteristic for a GaAs/AlAs device on n^+ substrate at 300 K. The device exhibits a peak current of ~16 mA at ~1.8 V which corresponds to a peak current density of ~160 kA/cm^2 for a 3.5 μm diameter diode. For larger size of the diodes, heating of the samples prevents us from

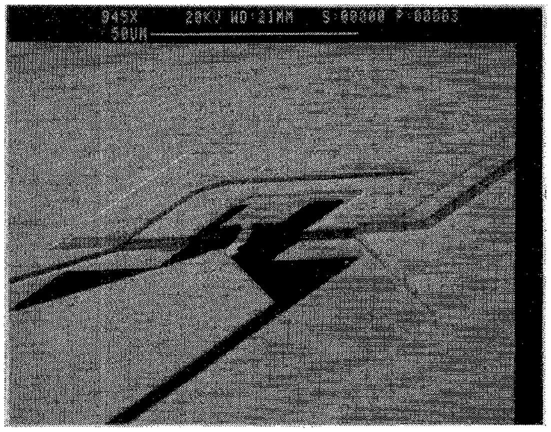

Fig. 2. Schematic cross section and SEM photo of the RTD fabricated in a planar technology.

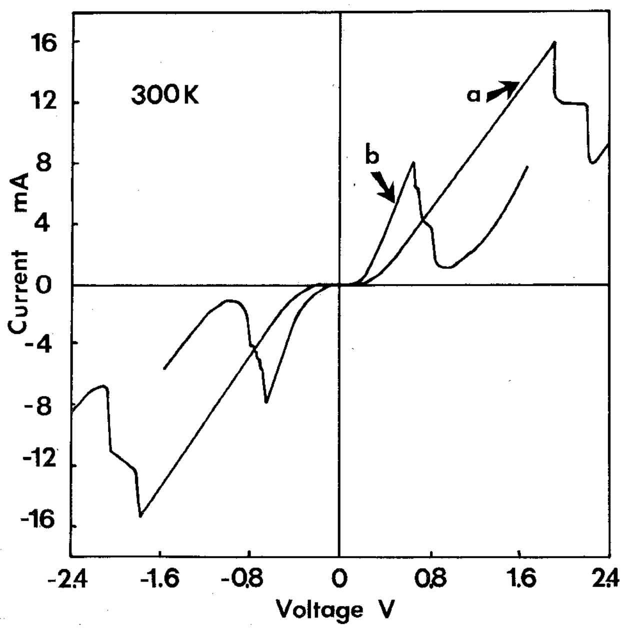

Fig. 3. Typical DC characteristics for a GaAs/AlAs device on n^+ substrate (a) and for a GaInAs/GaAs/AlAs pseudomorphic device on SI substrate (b).

achieving these densities. A typical dc characteristic for a device on SI substrate is displayed in Fig. 3(b). The device exhibits excellent characteristics with PVCR's as high as 6:1 along with simultaneously peak current density of 50 kA/cm^2 which compare favorably to the best published results [10], [11]. Note also the high degree of symmetry in the I–V curve which is a good indicator of quality interfaces.

Following our previous work [12], on-wafer reflection gain measurements were performed between 50 MHz and 40 GHz using cascade RF probes and an 85107 A HP network analyzer. Shown in Fig. 4 is the one port measurement of a vertically integrated sample. The active area is 20 μm^2. The diode is biased in the NDR region. Note that no de-embedding was used at this stage to correct for parasitics. For frequency evaluation, we used the equivalent circuit which consists of a single capacitor C_d with a parallel negative resistance R_d. These intrinsic lumped elements are completed by the parasitic capacitance C_p, the inductance Lp attributable to the bonding and Rs the overall series resistance. A good fit was obtained for $C_d = 36$ fF, $R_d = -172\,\Omega, R_s = 9\,\Omega, L_p = 60$ pH and $C_p = 13$ fF (air-bridge technology). With this set of data derived

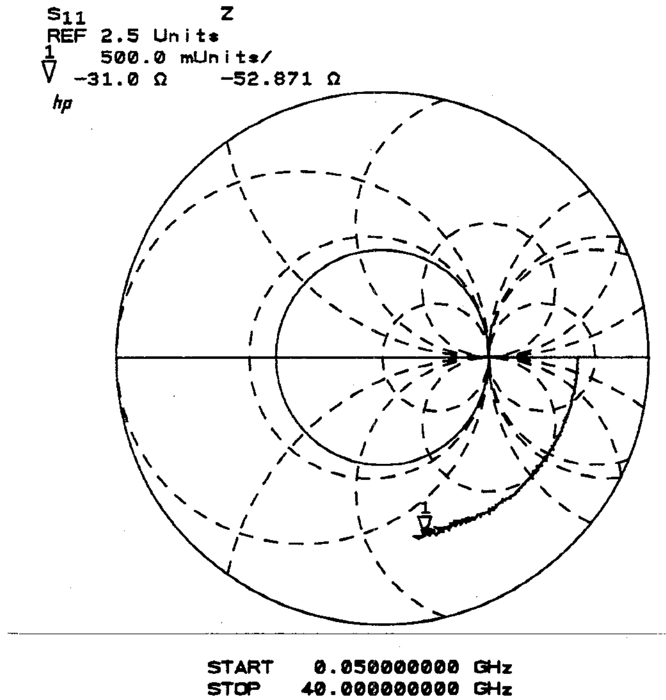

Fig. 4. One port measurement of the impedance. The bias is adjusted in the NDR region to satisfy the stability criteria.

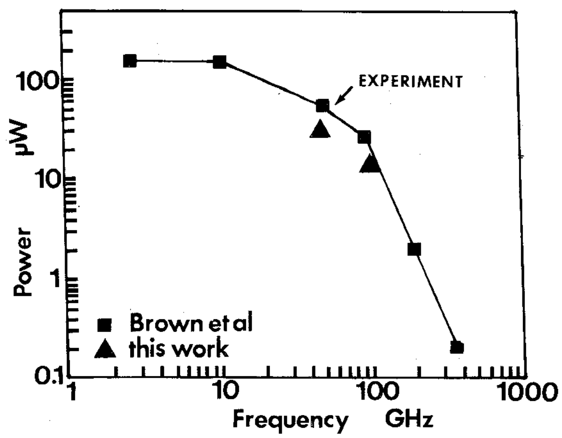

Fig. 5. Experimental powers for a 4 μm diameter diode from [13] and results from the present work for a 3.5 μm diameter diode.

from experiment, the cut off frequency for NDR is in excess of 100 GHz. This frequency is limited by the high impedance level needed to satisfy the stability criteria.

IV. Oscillator and Multiplier Results

The wafers on n^+ substrate were sawed into chips of $100 \times 100\,\mu$m^2 and mounted in a test waveguide for measuring the oscillator power at 35 and 110 GHz. The power levels measured at 300 K with a bolometer were 36 μW at 38.6 GHz and 12 μW at 110 GHz. Referring to the oscillator results from the published literature on AlGaAs based RTD's [13] given in Fig. 5 the output power are state of the art results.

For harmonic multiplication, the samples were mounted in a commercially available multiplier mount. The measurement set up has a quasi-optical scheme and was initially developed to study reactive species of astrophysical interest [14]. The diodes were driven by a

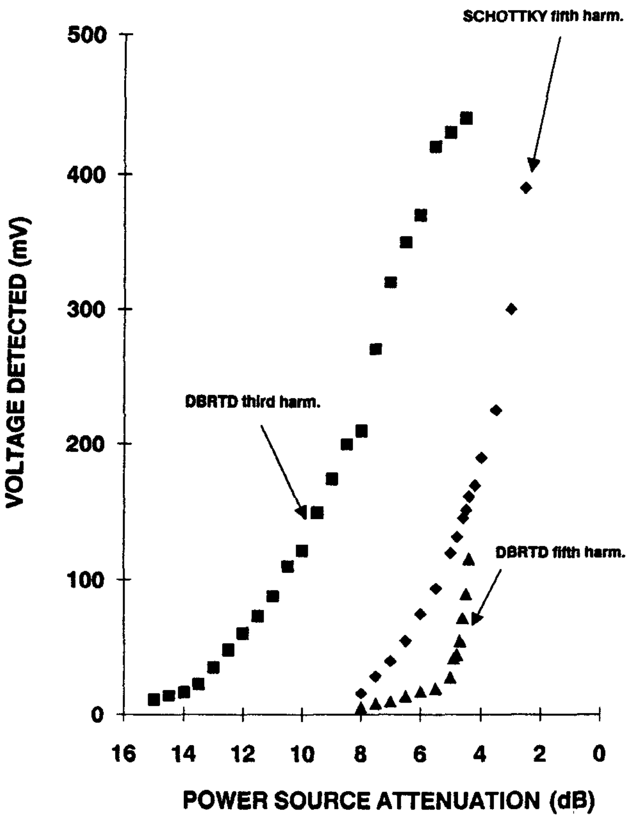

Fig. 6. Measured voltage of InSb detector against input power delivered by a klystron at 64 GHz.

klystron at 64 GHz and, in the output path, high filters enable one to spectrally analyze the power delivered by the diode. The receiver is a helium cooled InSb detector. Fig. 6 shows the power response at 3rd harmonic (192 GHz) and 5th harmonic (320 GHz). For comparison in terms of available power commercial Schottky diodes were also tested under the same experimental conditions. It is interesting to note that equivalent performances were obtained for both types of devices by increasing the multiplication order to frequency quintupling.

In the multiplier experiment the devices were unbiased and driven in the NDR region to take advantage of multiple extrema in the current waveform. This requirement can be unfavorable especially for high threshold voltage devices when input power is limited [14]. From this viewpoint, it is clear that pseudomorphic structures with a buried well may overcome partly this difficulty. From Fig. 3 it is apparent that a drastic decrease in the peak voltage 0.8 V instead of 1.8 V has been achieved by comparing structures A and B. In addition it can be noted that the PVCR's were enhanced. This suggests the superiority of these new tunneling devices for multiplication in view of the large harmonic content in the current and of the reduction of the amount of input power required to pump the diode.

V. Conclusion

High performance resonant tunneling diodes were successfully fabricated in a whisker contacted and in a planar technology. The RF capabilities of the diodes were demonstrated either by direct measurement of their small-signal impedance or by using them for oscillator and multiplier.

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