Microtechnologies for the monolithic fabrication of mm and submm non linear devices

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Abstract: We report on the recent development in microtechnology aimed at monolithically fabricating non linear devices at millimetre and submillimetre wavelengths. This approach will be illustrated with the fabrication of planar integrated Heterostructure Barrier Varactors and Schottky mixers for a use at 250 GHz and 500 GHz respectively. Also, epitaxial lift-off, followed by a transfer onto a host quartz substrate demonstrated here should permit us to further integrate the devices with the filtering and matching circuits in a monolithic fashion.

1. INTRODUCTION

The interest in the Terahertz gap is dramatically increasing nowadays with potential applications in the medical, environmental, space and telecommunication fields. From the solid state device side, three terminal devices have exhibited impressive cut-off frequencies up to 1 THz for a Heterostructure Bipolar Transistor, which was transferred onto a copper substrate [1] whereas maximum frequency of oscillation close to 600 GHz was demonstrated for Heterostructure Field Effect Transistors using a deep submicron gate technology and highly strained heteroepitaxy [2]. For two terminal devices, Heterostructure Barrier Varactors (HBV) have shown significant power generation in the 200-300 GHz frequency range [3]-[4] when used as harmonic multipliers and Schottky diodes [5] have demonstrated unrivalled mixing performances up to 2.5 THz [6]. Both devices have their intrinsic cut-off frequency far in the Terahertz frequency range. In this paper, we illustrate the main difficulties encountered in this challenge towards the extremely high frequencies with main emphasis on the technological challenges. The first remark is the recognition that the device in its circuit environment has to be thought as a whole. This means that a global approach, not only in the design with Computer Aided Design techniques but also in the fabrication aspects, has to be preferred. With respect to the fabrication issues, the technologies on nanometre and micron scales have to be involved with distinction between the active devices which scale as the electron wavelength and the passive devices, which compare to the electromagnetic wavelength.

Here we focus our attention on two specific devices namely a HBV tripler operating in the upper part of the millimetre waves (250GHz) and a mixer intended to operate at 500 GHz. Section 2 will be devoted to epilayer fabrication whereas section 3 deals with the device micro-technologies. Epitaxial-Lift-Off (ELO) followed by device transfer on quartz support of the embedding circuit will be considered in section 4. Concluding remarks on rf performances are discussed in section 5.

2. EPILAYER DESIGN AND FABRICATION

For illustration of the technologies on a nanometre scale, let us consider Figure 1, which shows a Scanning Electron Micrograph (SEM) of an heterostructure barrier device. The barrier was grown in order to stop any significant conduction mechanism. InP-based structures were grown in this laboratory using a Riber gas source MBE system In short, such a device operates in the varactor mode by taking benefit of depletion effect in the adjacent layer of a single barrier heterojunction. The former is constituted of a modulation doped region in order to satisfy the trade-offs between a highly doped contact region and a moderate-doped depletion region. In contrast a strong displacement current can be established through the depleted (capacitance) modulation region. This blocking process is achieved in reverse as well as in forward conditions. There is no rectification effect and a very advantageous symmetry is obtained in the C-V characteristics (only odd harmonics are generated).

Using a semiconductor (SC) crystalline barrier rather than a Metal/SC permits us to stack several barriers (epitaxial series integration of the diodes) on the same epitaxy, as it is exemplified in Fig. 1, with a high benefit in terms of voltage handling and decrease in capacitance level. This kind of heterostructure offer many ways of improvement in terms of band gap engineering. For example, we can greatly improve the non-linear properties by using different materials creating then quantum zones which affect the conduction relationship.

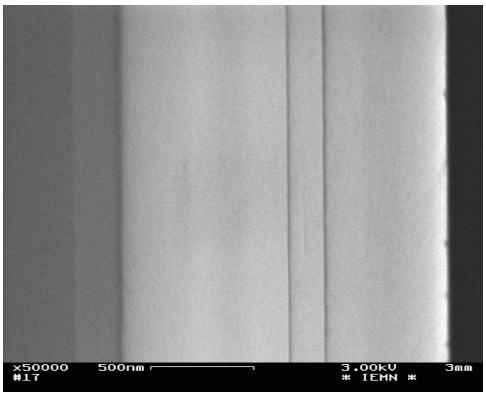

Fig. 1: SEM of a dual barrier Heterostructure Barrier Varactor. The AlAs layers appear in dark in the photo (1.5nm).

To alleviate the decrease in the capacitance ratio when we only varied the doping level of the depletion layer, the use of planar doping or pre- and post-well configurations can counterbalance this consequence. In both cases, the basic idea is to shorten the screening length by accumulating electrons closer to the barrier (quantum well scheme or delta doped concentration). Both techniques have respective advantages and drawbacks.

With respect to the I(V) characteristic, tunneling effects through the barrier are responsible for the leakage current at moderate voltages whereas the breakdown effect can be explained by impact ionization in the adjacent low gap layer.

Turning now to the Schottky mixing issue, here again the use of heterojunction can be of great help for reducing the saturation current for InP-based devices. Indeed low gap materials exhibit correlatively low built-in potential. Whereas these properties can be advantageous for low voltage driving conditions conversely the leakage current is high for a room temperature operation. The solution consists in inserting a wide gap layer between the Schottky metal and the narrow gap material enhancing by this way the apparent barrier height. The epilayer design was first conducted by extending to the Schottky diode case the in-house code developed earlier for quantum-devices. It appears very important to take into account all the conduction current contributions (as tunneling field emission for example.) to describe in a realistic way, the I-V characteristics of narrow gap materials. Good agreement was obtained between theory and experiment with, as expected, a threshold voltage for conduction onset quite low (V_{bi} ~ 0.15V). Also, varying the thickness permits us to modulate the conduction properties and the thickness of this epilayer has to be finely optimised (Fig. 2) with a critical balance between thermally-assisted tunnelling and resonant Fowler -Nordheim emission [7].

Basically the total conduction current is the result of three contributions : (i) pure tunneling from the highly populated states below the Fermi level, (ii) thermally assisted tunneling phenomena and (iii) thermionic emission over the InAlAs barrier. Quantum calculation does not need to make a distinction between these contributions and can be used to investigate the influence of the InAlAs layer. We can estimate each contribution by divided the current integral interval with different energy gap. So in figure 2, there clearly exists an optimum between an ultra thin barrier where pure tunneling current is dominant and a thick barrier where Fowler-Nordheim field emission is the significant factor.

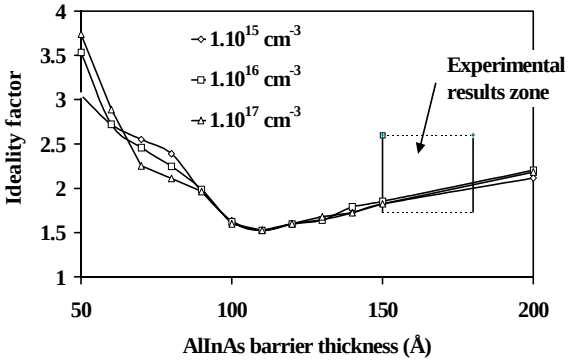

Fig. 2: Illustration of the design optimization for a Schottky metal/InAlAs/InGaAs lattice matched diode to InP substrate.

3. MICROTECHNOLOGIES FOR THE DEVICE FABRICATION

Several issues have to be addressed for the fabrication of devices aimed at operating in the Terahertz gap and first of all the requirement to minimize as far as possible the parasitic elements. This concerns all the series resistance terms (Rs), which are key factors of merit in the cut-off frequency but, also the reactance elements such as the self inductance and the pad-to-pad capacitance. The reduction of Rs has motivated various solutions including notably the development of finger shaped contact schemes. Such a technology can be very critical if the diode area has to be in the $1\mu m^2$ range as it is the case for a 500 GHz mixer. In practice this means that advanced technologies have to be employed involving a T-gate technology widely used in the fabrication of high frequency HEMT's and which becomes a generic technology for full planar devices as well as vertical devices such as HBT's or HBV's. Figure 3 illustrates this technology with the cross section of a T-shaped contact implemented onto a mesa (dual situation of a recessed HEMT). In our work, e-beam molds have been fabricated with a bi-layer electron resist (PMMA/copolymer) via an e-beam patterning at various doses. In this process, the width of the mesa was 0.5-1.5µm. Several patterns were realized with a typical area around $1\mu m^2$.

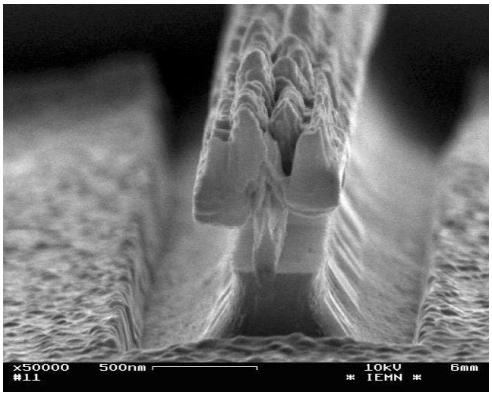

Fig. 3: SEM of the cross section of a T-gate (0.1x 10µm^2) contact implemented on top of a mesa

For the minimization of the reactive parts, an air-bridge technology is generally preferred to the dielectric crossover technique. In addition, this technology enables the further integration of the devices in an anti-parallel configuration such as that required for subharmonic mixing using Schottky devices. We demonstrated that several HBV's can also be planar integrated with an overall number of elemental devices of eight [8]. Fig. 4 shows the result of the batch for subharmonic mixers using antiparallel Schottky diodes. A deep etch was further made after the air-bridge completion in order to decrease the parasitic capacitance, which dramatically influences the down conversion efficiency.

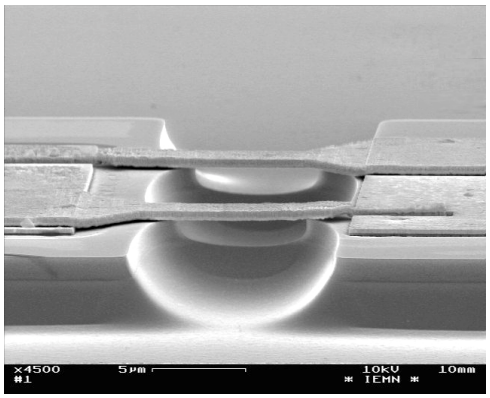

Fig. 4 SEM of deep submicron Schottky diodes (0.1x 10 µm^2) in antiparallel configuration

4. EPITAXIAL LIFT-OFF AND TRANSFER ON HOST SUBSTRATE

The motivation for transferring or grafting the devices onto a host substrate stems primarily from the high permittivity of the semiconductor substrate ($\varepsilon_r > 10$). This means that the electromagnetic energy is easily trapped within the substrate. A number of solutions exist notably by reducing as far as possible the dimensions of the chips by dicing and lapping. At the moment, the nominal chip dimensions are ~200x100x50 µm^3 and further shrinking of these dimensions becomes troublesome. On the basis of these considerations, we have recently demonstrated the possibility to lift-off the devices and to report the epilayer material such as that shown in Fig. 1 prior to the device process on a glass or quartz substrate [9]-[10]. For the ELO process, we took benefit of the quasi-infinite selectivity between InP and the InGaAs/InAlAs epilayers. In order to remove the InP substrate, a HCl:H_2O selective etch solution is used. This solution has been seen to have an high etch rate selectivity ratio of up to 500 between InGaAs and InP. For the grafting process, we used a thin film of Epon SU-8 in order to transfer the layers onto the substrate (Fig. 5). Another advantage afforded by the report stage with an up-side down stage during fabrication is the possibility to preserve a quasi vertical configuration. Indeed it is now well recognized that a major degradation of the series resistance stems from the so-called "spreading resistance" effects. By the deposition of a thick metal material on the capping layer prior to the grafting a vertical configuration of current lines can be maintained throughout the device thus avoiding side contact effects.

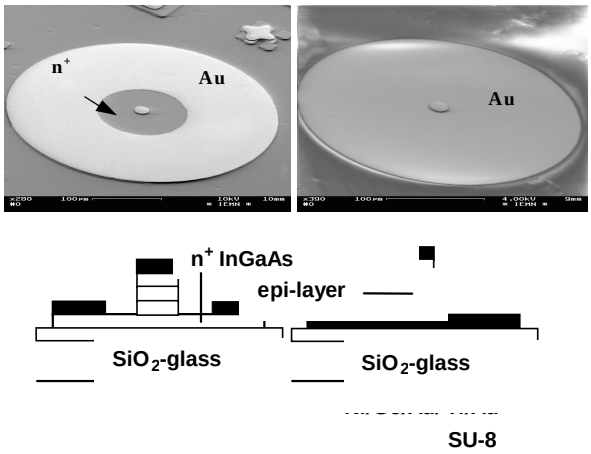

Fig. 5 Illustration of ELO devices and transfer techniques applied to the report of the HBV's onto a quartz substrate (Side contact in type I configuration, quasi vertical scheme in type II configuration).

5. DISCUSSION ON RF PERFORMANCES

In order to illustrate the benefits resulting from the nanotechnologies and microtechnologies reported above, let us now consider more specially HBV's. As a matter of illustration, Figure 6 shows the frequency dependence of the diode impedance measured at room temperature up to 40 GHz for type I and type II devices (see Fig. 5). For the RF measurements, RF probes were placed directly onto the devices which had been fabricated, as previously mentioned, in a coaxial-type configuration. Under these conditions, it has been previously demonstrated that the device intrinsic elements, which describe the electrical

behaviour of the diodes, can be accurately determined without the necessity of a de-embedding procedure. Notably, the parasitic 'pad-to-pad' capacitance and self-inductance due to the interconnections were found to be negligible. It can be seen that the corresponding series resistance of type II device is extremely low (0.5 Ω), a welcome feature for subsequent high frequency operation. By this way, cut-off frequency in the Terahertz range were estimated.

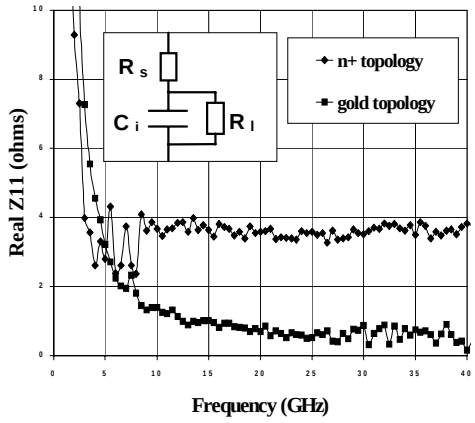

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Fig.6 Variation of the Real part of the diode impedance as a function of frequency. Rs can be directly measured

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Figure 7 shows the output power and conversion efficiency, which were measured at 250 GHz for two integrated devices using a Carcinotron pumping source. Two diodes were series interconnected which means that a total number of four barriers were cascaded. It can be shown that the capacitance at zero-bias voltage was between 1 and 1.7 fF/μm^2 for a capacitance ratio of 5 to 7:1 depending on the doping concentration. With respect to the voltage handling, the breakdown voltage per barrier was of the order of 6V. This means that the devices can be pumped 'safely' with a peak-to-peak voltage swing of about 20 V explaining the quite good performance in terms of power. It can be seen from Fig. 7 that a maximum output power around 10 mW can be achieved for a pumping power in the 100 mW range without saturation effects. The maximum conversion efficiency is 12% in a large input power scale with a rather flat behaviour. These unrivalled performances are a direct consequence of the power and frequency capability of the devices [11]. Moreover, the InP-based devices are less sensitive of thermal degradation effect, which will occur at high power pump.

6. CONCLUSION

Microtechnologies have introduced a profound change in the fabrication of Terahertz devices with numerous improvements in terms of functionality, performance and easiness in the manufacturing. One of the common denominator is the systematic use of

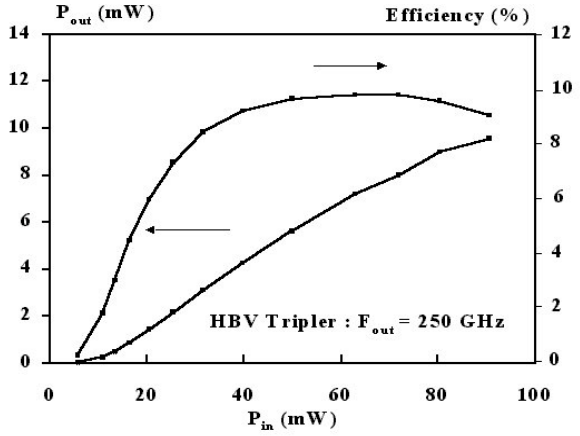

Fig. 7: Output power and conversion efficiency of a discrete HBV device measured at 250 GHz.

heterojunctions which enables us in particular to tailor the electrical properties of the epilayers. However, very advanced techniques have to be employed for the device fabrication with the goal to fully integrate the samples within the circuit in a 3D monolithic fashion. Epitaxial stacking, planar integration, transfer technique and micromachining would be the main procedures to reach the fabrication of far infrared circuit

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