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Recent progress in the Development of French THz Schottky Diodes for Astrophysics, Planetology and Atmospheric Study

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Abstract—**During the last 10 years the LERMA-Observatoire de Paris in close collaboration with C2N has made a great progress in the development of the French technology of THz electronic components based on Schottky diodes. By bringing together the unique knowledge and skills of both laboratories, we have developed the submillimeter devices at 300GHz, 600GHz and 1.2 THz, with state-of-the-art performances. These devices are selected today for the submillimeter wave instrument (SWI) instrument of the Jupiter Icy moon Explorer (JUICE) satellite, ESA's first class L mission. The progress made over the last years and our future work on the device miniaturization and increasing working frequency will be discussed in this presentation.**

I. INTRODUCTION

MILLIMETER and submillimeter heterodyne observations could help us to improve the understanding of the universe, the solar system and the planet's atmosphere. Among different available technologies to build THz and sub-THz devices for radio-astronomy, planar GaAs Schottky diodes play a crucial role. In particular, this technology enables the building of high frequency multipliers with sufficient output power and low noise mixers, both working at room temperature or at cryogenic temperature and capable of reaching the THz region [1].

II. FRENCH THZ SCHOTTKY DIODE PROCESS

In 2006, LERMA — in close collaboration with C2N (formerly LPN) — started the development of GaAs-based planar Schottky nano-diode fabrication technology.

Approaching the THz frequencies, parasitic capacitances (dielectric substrate losses, pad-to-pad capacitance, and finger-to-pad capacitance), series resistance and velocity saturation, start to affect the performances of planar Schottky-diode-based mixer and multipliers, and made the fabrication process challenging. The dielectric losses could be partially decreased by reducing the substrate thickness to a few microns (membrane-based diodes). The use of air-bridge connection between anode and other parts of the circuits allows to reduce the finger-to-pad capacitance if the air-bridge is sufficiently vertical. The series resistance can be controlled by the distance between anode and ohmic contact and by increasing of doping level to $5\text{x}10^{17}$ cm^{-3}. Moreover, in order to reduce the junction capacitance and to increase the cut-off frequency the anode area should be decreased down to the submicron size. All these parameters should be taken into account during the fabrication process.

The manufacturing of Schottky-based components is made in C2N's clean room that has all necessary equipment for complete Schottky diode fabrication, including the epitaxy of the active layer on GaAs substrate. In order to reach THz frequencies, we have developed a fabrication process, which is fully based on e-beam lithography, and allows a high precision on small structures (anode size less than $0.1\mu\text{m}^2$) and gives a great flexibility for monolithic microwave integrated circuit (MMIC) designs. An important effort has been made during the last years in order to improve our technology and manufacture the diodes with excellent characteristics and very good homogeneity across the wafer

The active diode layers and GaAs membrane are grown at C2N by Molecular Beam Epitaxy (MBE) technique on 500μm-thick semi-insulating 2-inch GaAs wafer. First, a 300-450 nm AlGaAs etch-stop layer is grown, followed by 2-5 μm-thick (depending on application) GaAs semi-insulating membrane. This has been followed by 50 nm AlGaAs etch-stop layer and 700 nm heavily doped $5\text{x}10^{18}$ cm-3 n^{++} layer. The thickness and the doping level of the n epi-layer are adapted according to the chosen application (mixers or multipliers) and working frequency ranges.

The fist fabrication step consists in dry etching of n and n++ GaAs and 50-nm AlGaAs layers in Cl_2-based inductively coupled plasma (ICP) in order to form the mesas. The using of ICP instead of wet etching allows a better control of the mesa size and verticality of mesa sidewalls. Then the ohmic contact is formed on the top of the mesas. The n epi-layer is etched down to n^{++} layer in H_3PO_4:H_2O_2:H_2O solution. The Ni/Ge/Au/Ni/Au metal films are successively evaporated and rapid thermal annealing is performed at Ar-H_2 environment. Then anode is formed by evaporation of Ti/Pt/Au metal films on the top of the mesas and protected by a 50 nm of Si_3N_4 dielectric films deposited in plasma enhanced chemical vapor deposition (PECVD) reactor. The next step consists in the formation of the air-bridge connections. The challenge is to form the connection to the anode to be as vertical as possible (Fig 2b) in order to reduce the parasitic capacitance. The 2μm-thick LOR resist is deposited and reflowed in order to form the support for the air-bridge. The Si_3N_4 passivation on anode is opened by SF_6-based reactive ion etching (RIE) plasma and air-bridge fingers are formed by evaporation of a 600-nm-thick gold metal film. After this step, the diodes are passivated again by 50 nm Si_3N_4 film in PECVD reactor. Then the circuits are separated by etching of the GaAs membrane (2-5 μm) down to the AlGaAs etch-stop layer in HBr-based ICP

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plasma [2]. Then the wafer is protected by the resist, mounted topside-down onto the quartz support and chemically thinned down to the membrane. Finally the circuits are released in acetone and mounted in the micro-machined wave-guide blocks.

Our first success in 2012 was the realization of the discrete anti-parallel pairs of diodes with an anode size of 0.5 μm^2 (Fig. 1a). These diodes demonstrated the very good electrical characteristics (ideality factor n=1.15-1.19, serial resistance Rs = 10-15 Ohm) and were tested by Radiometer Physics GmbH (Germany) on a 664GHz sub-harmonic mixer. A double side band receiver equivalent noise temperature of 1600K was measured at room temperature with an IF LNA in the 0.5-8GHz band.

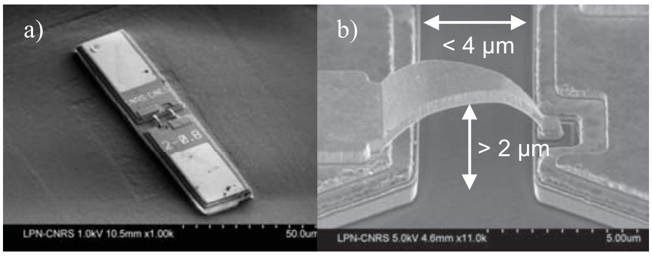

Fig.1. SEM image of antiparallel pair of discreet Schottky diode. a) Released diode on carbon membrane. b) Zoom on air-bridge connection.

Based on these very promising results we started the development of Schottky-diode-based MMIC integrating the diode cell and matching network on few microns thick GaAs membrane. In order to easily mount and maintain the MMIC circuits in metal wave-guide block, the 1-2µm-thick Au beam-leads are formed by the same technique as for air-bridge fingers. Figure 2 shows an example of the beam-lead connection on our first MMIC 320GHz frequency doubler.

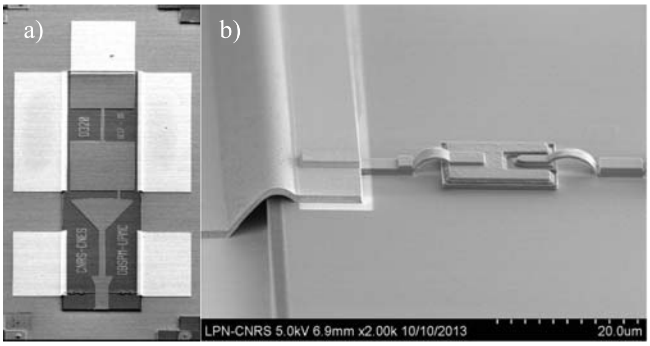

Fig. 2. SEM image of 320 GHz MMIC doubler. a) Whole structure; b) Zoom on air-bridge and beam-lead connection.

In 2015, we have demonstrated state-of-the-art noise performance on our first MMIC 600GHz subharmonic mixer [3]. At 295 K ambient temperature, an average of 1284 K DSB receiver noise temperature was measured over the 520–620 GHz frequency range. A record 1130 K minimum DSB receiver noise temperature at 557 GHz was measured. At 134 K ambient temperature, an average DSB receiver noise temperature of 685 K from 538 to 600 GHz was measured when correcting for the cryostat window loss. A minimum DSB receiver noise of 585 K was measured at an RF center frequency of 540 GHz.

In 2016-2017, we have built our first 1200GHz receiver for the SWI on ESA JUICE planetary probe. The record receiver sensitivities were obtained in the 1080-1280GHz band at room temperature and at cryogenic temperature [4].

Table1 1: LERMA-C2N mixer diodes characteristics and RF performances

Circuit / diode type	Frequency range (GHz)	Anode area, doping, series resistance, capacitance and substrate thickness	Performance at room temperature	Performance at 130-150K
2012-discrete anti-parallel pair - unbiased	664	0.5µm2 2E17 cm^{-3} $R_s \simeq 57\Omega$ C_{j0}=0.8fF GaAs 3µm	T_{mixer_DSB} =1600K G_{mixer_DSB} = -8dB	Not measured
2015 - 600GHz SHM - unbiased	520-620	0.5μm^2 3E17 cm^{-3} $R_s \simeq 32\Omega$ C_{j0}=1.1fF GaAs 4µm	$T_{Receiver\_DSB}$ $\in$[1030,1700]	$T_{Receiver\_DSB}$ $\in$[540,1080]
2017 - 1200GHz sub-harmonic mixer - biased	1080-1275	0.16μm^2 5E17 cm^{-3} $R_s \simeq 45\Omega$ C_{j0}=0.5fF GaAs 2µm	$T_{Receiver\_DSB}$ $\in$[3280, 6320]K with an average of 3840K	$T_{Receiver\_DSB}$ $\in$[1600, 2570]K with an average of 1950K
2017 – 2THz discrete anti-parallel pair - unbiased	1.8-2THz	0.07µm2 5E17 cm^{-3} $R_s \simeq 75\Omega$ C_{j0}=0.3fF GaAs 2µm	Not measured (test diodes)	Not measured (test diodes)

III. ACKNOWLEDGMENT

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