Integrated Schottky Structures for THz-Applications

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Abstract — **A novel fabrication process was developed for Schottky-based integrated structures. The process aims to achieve ultimate performance at millimeter (mm) and Sub-millimeter (Sub-mm) wavelengths. Excellent performance was realized in several Sub-mm-modules. Achieved results represent European state-of-the-art performance at these frequencies.**

I. Introduction

Schottky diodes are generic components that are used in practically all non-cryogenic millimetre and sub-millimetre wave receivers in Earth Observation and Space Science. They are especially critical to future Earth observation instruments operating at sub-millimetre waves in space missions like CIWSIR, GOMAS, PREMIER, and MetOp. These systems cover frequencies up to 664 GHz but high-performance non-cryogenic receivers at 1THz and above may be required for future Earth Observation and Space Science instruments.

At frequencies above around 300GHz, parasitic capacitances close to the Schottky contact start to become extremely important to the overall performance of the mixer or multiplier. The conventional method of reducing these effects in Schottky diodes involves making the anode fingers as air-bridges which span a "surface channel" in the GaAs. Unfortunately the lengths of these air-bridges are also a limiting factor because of in-line inductance. Some ingenuity is therefore required to overcome these difficulties. For multiplier design, it is especially important that there is not too much capacitive coupling from the diodes themselves to the waveguide wall or to the central transmission line. Unfortunately, in the doubler circuit, one needs to place a capacitive tuning element quite close to the diodes to counteract the effect of lead inductance, but this element must not interact with the diodes themselves. For any type of balanced multiplier, the diodes must also be well balanced with respect to the input and output signals. This requires the diodes be very similar, in terms of absolute capacitance and also have the same parasitic couplings to the rest of the circuit.

The use of a highly integrated circuit, which includes not only all the diodes but the coupling structures helps achieve accurate placement of the diodes, with respect to the transmission line and waveguide walls, but also with respect to each other. Performance reproducibility is excellent in these structures as there is very little variation in the geometry from device to device. All that is required is that the fairly large integrated structure be mounted in the waveguide block and the block closed.

The use of integrated circuits above 700GHz in the most optimized designs is unavoidable anyway, as the physical dimensions of the waveguide and substrate channel become extremely challenging for even the thinnest practicable substrates to be used (quartz around 20um).

If a membrane integrated circuit is used, it is important that the membrane is extremely thin, use low dielectric constant material and is not excessively fragile. Unfortunately, if one uses GaAs as the membrane material itself, it fails in all three categories, as it is difficult to make stress-free thin membranes, is very breakable and has a high dielectric constant (near 13). The only benefit from using GaAs is that it is part of the semiconducting wafer and can be integrated monolithically.

A better solution is to use a transferred membrane substrate. In this case the membrane material is not related to the semiconductor wafer and can be chosen with low dielectric constant and appropriate mechanical characteristics.

The technology developed by ACST achieves these goals and results in a thin stress-free membrane, which is extremely robust and is radiation tolerant. Because the dielectric constant is low, variations in the thickness or absolute value of the dielectric constant of the membrane have minimal effect to the circuit compared to a higher dielectric constant material, so geometrical tolerances are far less critical.

II. Film-Diode Process

Film-Diode (FD) Process represents a new technology platform for fabrication of both discrete diodes and integrated circuits for mm/Sub-mm-Wave applications. The FD-structures consist of a few-micrometer thin transferred membrane-substrate, which maintains robustness of all circuit elements. This approach aims at ultimate performance at mm and Sub-mm-waves.

The FD-process implies two-side processing of the semiconductor wafer. Schottky-contacts are formed on the front-side of the epilayer whereas back-side processing offers opportunity for ohmic metallization directly under the corresponding Schottky contacts. The main advantages of such an approach is improved thermal dissipation and uniform distribution of current density across anode area. Moreover, two-side processing offers opportunity for 2.5-D integration. This implies more flexibility for device miniaturizing, which is especially useful for high frequency

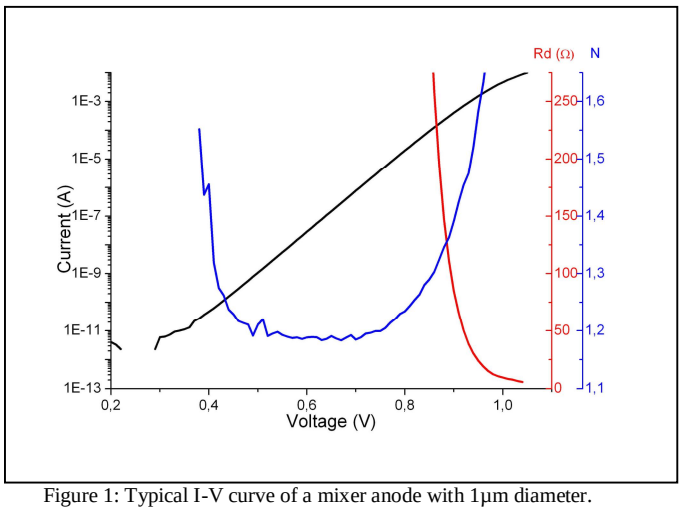

Figure 1: Typical I-V curve of a mixer anode with 1µm diameter.

applications. A thin membrane-substrate allows one to drastically reduce substrate-related circuit-parasitics and RF-losses. The membrane-substrate is mechanically very robust and optically-transparent. This significantly facilitates assembly process. FD-structures can be assembled either by soldering or gluing on corresponding contact-pars or can be suspended on gold-beamleads, which is the best approach for suspended-substrate mounted in waveguide technology.

Various circuit architectures can be accommodated by the FD-process, including fabrication of single diodes, various diode arrays, and passive circuit elements including capacitors, resistors, and surrounding circuitry like transmission lines, filters, matching networks etc.

III. DC-CHARACTERISTICS

DC-characteristics were extracted from on-wafer I-V and C-V measurements using Agilent 4156A Parameter Analyzer and Agilent 4284A C-V-meter, respectively.

A. Mixer anodes

Typical I-V-curve of a mixer anode with diameter of 1.0µm is plotted in Fig. 1. Ideality factor (N) and differential resistance Rd are a function of the applied voltage as plotted in the figure.

Fig. 2 summarizes relative Series Resistance (R_s)-values versus ideality factor for mixer diodes with several anode diameters from different batches. Relative R_s-values are determined for each anode from on-wafer measurements. They are called "relative" because temperature effects during I-V measurements are not considered and, therefore values can differ from absolute R_s-value. Nevertheless, obtained values do strongly correlate with anode diameters and can be used for comparative evaluation. Fig. 2 shows a good uniformity of anode characteristics across the wafer. Both series resistance and ideality factor obviously increase with reducing anode diameter. This tendency does not contradict our expectations. Similar results were obtained

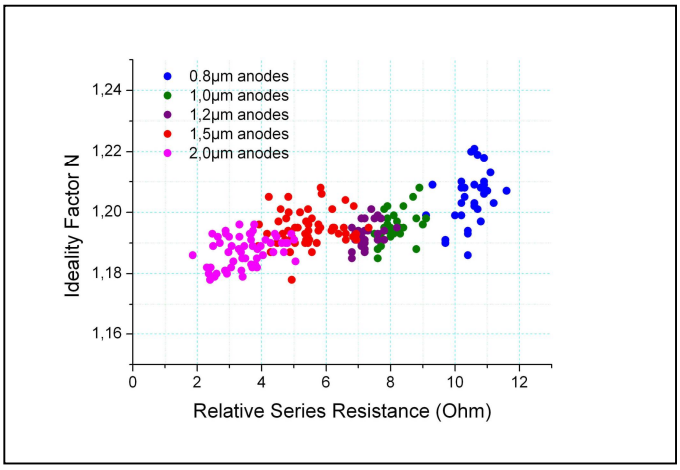

Figure 2: Summarized relative Rs-values versus ideality factor for mixer anodes with several anode diameters from different batches.

from different batches, which suggest good process reproducibility.

B. Varactor anodes

DC-characterization of varactor anodes includes both forward and backward I-V-measurements and evaluation of zero-voltage junction capacitance (C_{j0}). The breakdown voltage (U_{bd}) represents the backward voltage bias point where current exceeds 100nA. Due to optimized fabrication process, breakdown voltage of our varactors is unusually high and close to the theoretical limit considering doping profile.

I-V curves of several varactor diodes with similar anode sizes are plotted in Fig. 3. Some steps of backward I-V-curves are attributed to measurement errors of the parameter analyzer when automatically changing the current ranges. In the rest, plotted I-V curves are nearly ideal. The current increases exponentially under forward voltage bias and is very small and nearly voltage independent under backward bias. The reverse current steeply increases when voltage approaches breakdown value.

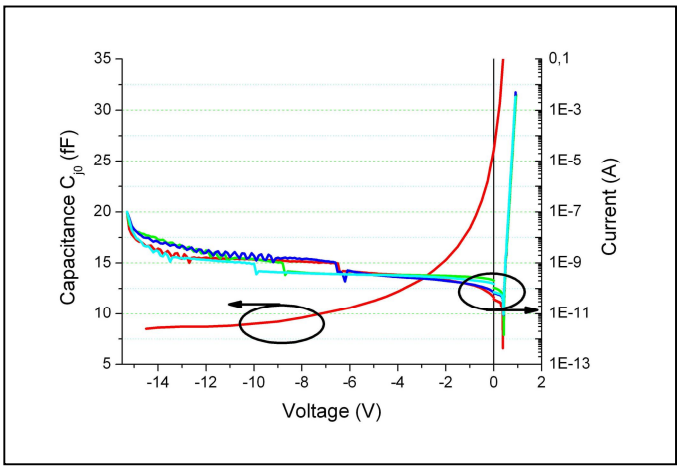

Figure 3: Typical C-V-curve and I-V curves of varactor diodes

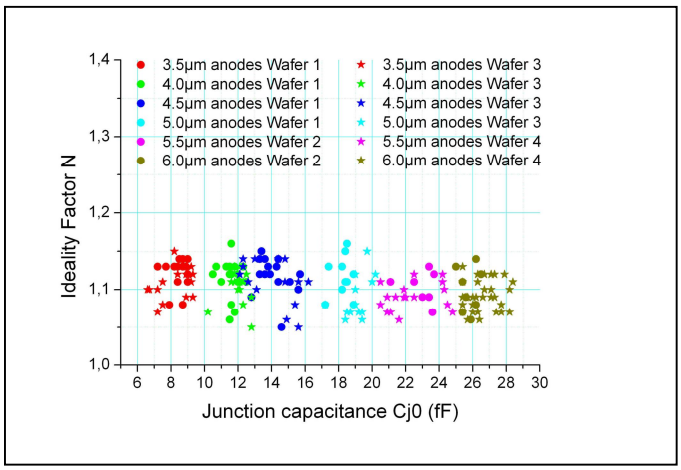

Figure 4: Summarized Cjo values for several anodes diameters from different batches.

Typical C-V characteristic of a varactor anode is also plotted in Fig. 3. Capacitance modulation factor (C_{max}/C_{min}) of these anodes is about 3.5, which is close to the theoretical model and is a good value for GaAs diodes.

Fig. 4 summarizes the C_{j0} values for several fabricated wafers with different anode diameters. Relative scattering of ideality factor value is because of short integration time set on Agilent 4156A Parameter Analyzer during I-V-measurements. With a longer integration time the I-V-curve looks much smoother and ideality factor can be estimated more precisely.

Wafers #1 and #2 are similar and include anode diameters of 3.5µm, 4.0µm, 4.5µm, and 5.0µm, whereas wafers #3 and #4 provide anodes with diameters of 5.5µm, and 6.0µm. Cj0-values strongly correlate to the corresponding anode size and cover values from about 7fF up to about 28fF for the various anode sizes. Cj0-value of anodes with similar diameter typically scatter within ±2fF but this deviation is within measurement accuracy.

IV. RF-CHARACTERIZATION

Several mm/Sub-mm wave modules have recently been developed and characterized, including sub-harmonically-pumped mixer (SHM) and frequency multipliers. Some developments were supported by R&D-projects while others were driven by commercial applications and are therefore, optimized more for reproducibility and reliability.. Frequency multipliers were mainly designed as Local Oscillators (LO) sources for SHM. They therefore provide moderate output power, rarely exceeding 10dBm. This section shortly describes some of the most recent developments.

A. 332GHz doubler IC

Fig. 5 shows a doubler IC placed on a glass carrier. The output coupler is rather thin and long. Therefore, handling procedures of this structure appears very tricky. In fact, the output coupler consists on thin SiONx layer, which is sandwiched between two metallic layers. This considerably improves elasticity of the output coupler and simplifies

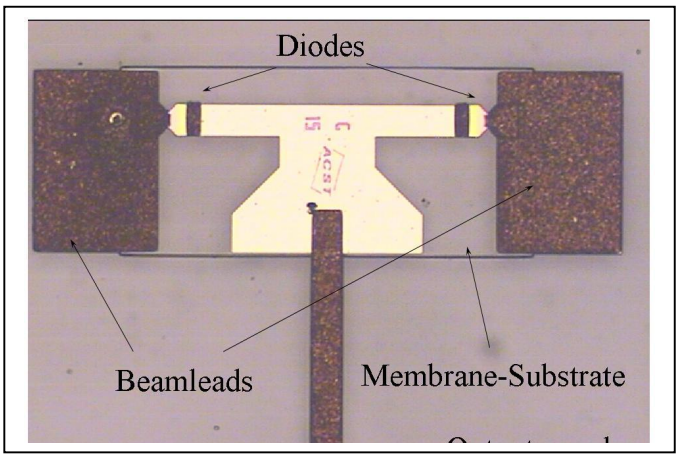

Figure 5: Fabricated 332GHz doubler IC placed on a glass carrier.

handling procedures. The doubler IC is realized using a balanced doubler approach with only one high breakdown-voltage varactor diode per arm. The diodes are connected in anti-series (DC) and are suspended on beamleads directly in the input waveguide. This approach allows thermal coupling of the anode mesa through the massive metallic beamleads to the WG-block, which represents a good heatsink for the dissipated power. Power handling capability of such a structure is in the order of several tens of mW. Output power well exceeds minimal LO-requirements of a SHM and is achieved at high efficiency.

A 166GHz power source was used to pump the 332GHz doubler for RF-characterization. Available output power of the 166GHz source was around 40 to 50mW. Fig. 6 shows measurement results. The doubler provides output power up to 14mW with a peak efficiency of about 30%. Standing-wave variations with 8GHz between peaks and are attributed to the mismatch between the input stage and the 166GHz source at a frequency spacing of C/2d. 'd' is therefore calculated to be

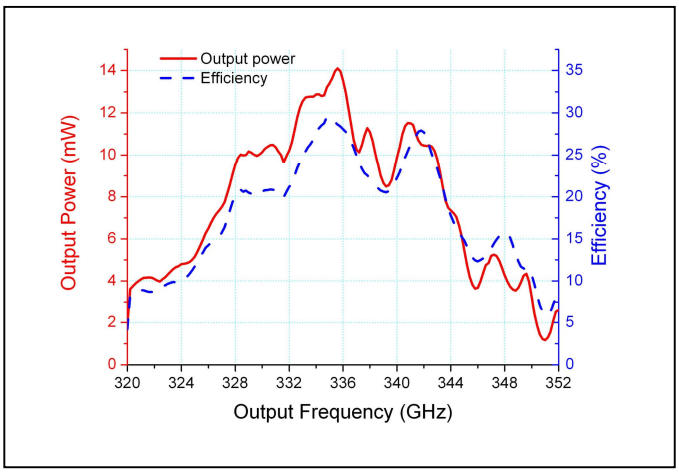

Figure 6: Output power and efficiency versus frequency of a realized doubler.

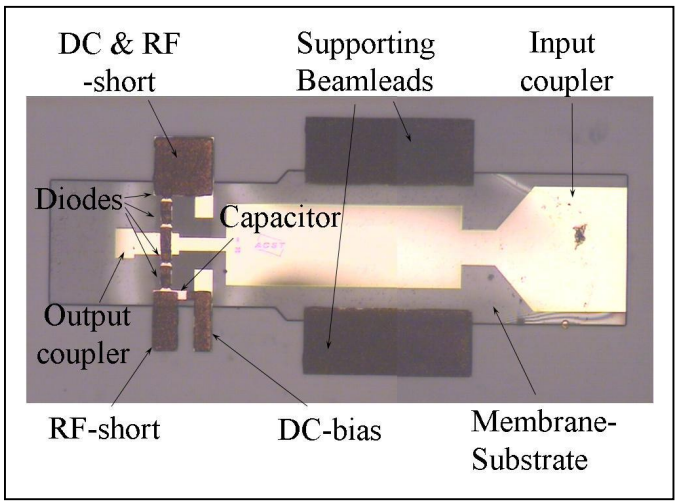

Figure 7: Fabricated 332GHz tripler IC placed on GelPak.

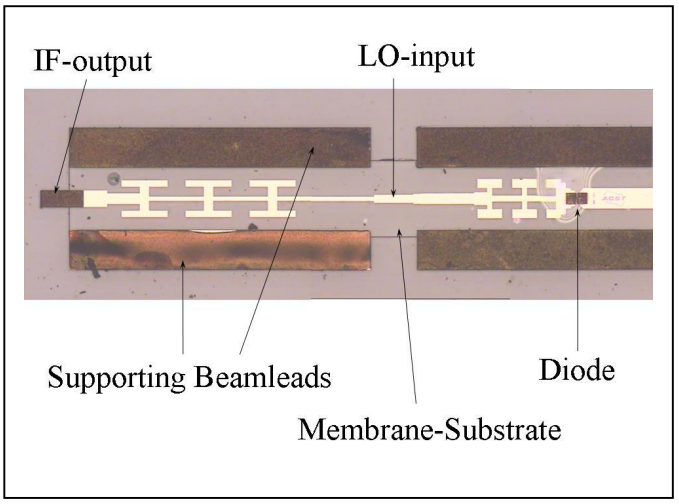

Figure 8: Optical view of a 664GHz mixer IC packed on GelPak.

approx. 18.75 mm (free space value for C) which fits in with the inter-doubler distance. The standing wave is easily shifted by adding a metal shim to increase 'd', as was confirmed by a independently -performed test.

B. 332GHz tripler IC

A 332GHz tripler was also constructed based on a balanced tripler approach with two varactor anodes per arm (4 total). The tripler uses a 110GHz high power source. Thermal dissipation from all varactor anodes required particular efforts but this is a separate topic.

An optical view of a fabricated tripler circuit is shown in Fig. 7. The DC-bias is separated from the RF-short by an integrated capacitor. This tripler provides up to 8mW of output power with a peak efficiency of more than 8%.

C. 664GHz mixer IC

A 664GHz Sub-harmonic mixer was also fabricated. The 664GHz mixer circuit consists of an anti-parallel diode pair monolithically integrated with surrounding circuitry on a transferred membrane substrate. Fig. 8 shows an optical view of a 664GHz mixer IC placed back-side-up on GelPak. The membrane-substrate strongly adheres to the GelPak surface. A small air bubble between the GelPak and Film-Substrate causes an interference patterns near the diode region. The IF-output lead is free-standing. This facilitates mounting either by bonding, soldering, or gluing on conductive epoxy. Wide lateral beamleads are also free-standing and serve to support the membrane as suspended-substrate approach in a waveguide block. RF-coupler and DC-short are not shown here because they are considered sensitive design features.

Fig. 9 demonstrates the planarity of the fabricated integrated circuits on membrane-substrate. A side view is shown of a free-standing mixer-IC with the focus on a lateral beamlead. Fabricated IC-s are very elastic due to the mechanical properties of the very thin membrane-substrate and are virtually stress-free.

Two mixers were RF-characterized and provided similar performance. This demonstrates good reproducibility of the developed fabrication process and employed WG-technology. Fig. 10 shows the RF-characterization results. The mixer performance is well in line with simulation results. As expected mixer temperature (T_{mix}) is under 1700K and conversion loss around 8.0 to 8.5dB (DSB). Optimal LO-power is around 4 to 4.5mW at 332GHz, which is very low for this frequency and can be supplied by either doubler or tripler considered in this work.

All measurements of the mixer use uncorrected data and include waveguide/horn losses and IF mismatch losses. At these frequencies, waveguide loss is considerable and probably accounts for several dBs of extra loss to the horn and in the horn itself. According to authors' best knowledge, this is the best result worldwide to date, as this frequency.

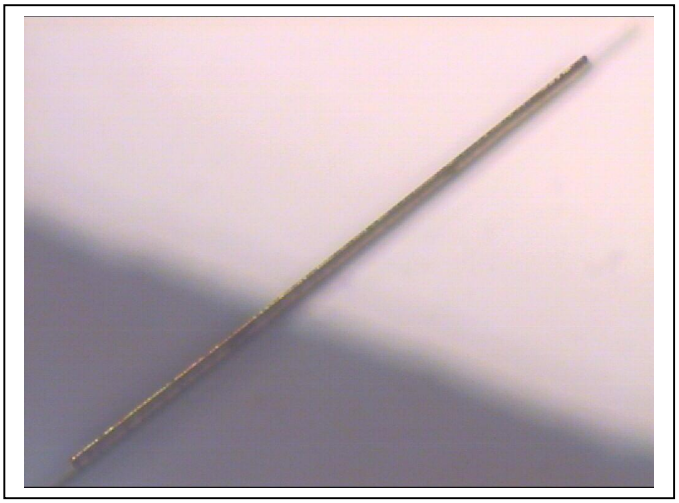

Figure 9: Side-view of a free-standing mixer IC with a focuse on a lateral beamlead.

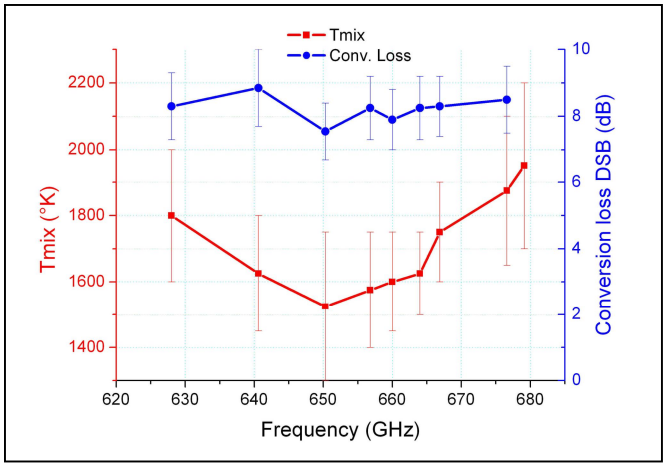

Figure 10: Measured performance of the 664GHz mixer.

V. Conclusions

A new fabrication process was developed for integrated Schottky structures, which aims at ultimate performance at mm and Sub-mm wavelengths. Electrical parameters of fabricated devices are well controlled. Systematic evaluation suggests good process reproducibility, which makes the process suitable for commercial and space use.

Several circuit designs were successfully implemented and tested, including a 332GHz doubler, a 332GHz tripler and a 664GHz mixer. Frequency multipliers were designed in such a way that they can be combined with the mixer to build a complete heterodyne receiver. All modules demonstrated excellent performance. The combination of the 332GHz tripler and 664GHz SHM represents the first all-European heterodyne receiver at this frequency. The fabricated mixer provides Tmix of below 1700K and conversion loss below 8.5dB (DSB) at optimal LO-power of about 4mW. According to authors' best knowledge, this is the best result worldwide to date, as this frequency.

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