Chapter 38
Fabrication of Planar Sub-Micron Schottky Diodes for Terahertz Imaging Applications

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Abstract Imaging sensors employing sub-millimeter waves and terahertz radiation (frequencies from 100 to 3000 GHz) are needed for security applications requiring stand-off, non-destructive sensing, due to its much larger penetration depth into dielectric materials.

38.1 Introduction

Imaging sensors employing radiation at frequencies beyond the visible range are crucial in security applications, as threats may come from concealed objects which cannot be detected by visual inspection. Microwave devices using radiofrequency (RF) up to several tens of GHz are currently employed for security sensing (e.g. in RF metal detectors and in body scanners), but they can hardly detect the shape of the concealed object, as the resolution of microwave imaging is limited by diffraction, and they cannot provide substance-specific contrast due to the lack of spectral signatures in the microwave range. Therefore, there is a considerable effort to bring concepts and devices from both the microwave and the infrared range towards the terahertz range, which sits in between them, with the aim of performing standoff imaging of concealed objects [1].

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In this paper, we present a process for the fabrication of Schottky diodes which can operate in the terahertz range. The diode is based on a Ti/*n*-GaAs junction with very low junction capacitance. For operation as terahertz sensor, the signal is fed to the diode through an on-chip terahertz antenna, and the diode can be used either as video detector, hence providing, after a low-pass filter, a dc output proportional to the intensity of the radiation power [2], or as mixer, with a local oscillator beam quasi-optically coupled to the same antenna [3]. Indeed, commercial Schottky diodes are currently employed as RF sensors up to 100 GHz, but their fabrication process has to be strongly modified to make them sensitive to terahertz radiation, as we will show in this paper. Furthermore, our process is fully planar, in order to fabricate monolithic matrixes of radiation detectors which could then be used to acquire real-time terahertz images in a focal plane array configuration, similar to infrared vision devices or digital cameras.

38.2 Device Design

The main parameter which limits the operation frequency of the Schottky diode is the junction capacitance, which is proportional to the junction area. We will show below that sub-micron junctions are needed for terahertz operation, which can be fabricated by high-resolution electron-beam lithography, instead of conventional optical lithography. Parasitic capacitances between the contact pads should be minimized by physically decoupling the contact pads, leaving metal microbridges for connection between them. A third parameter which limits the cutoff frequency is the series resistance, which can be reduced by using high-electron mobility Gallium Arsenide (GaAs) epitaxial layers as the semiconductor material, instead of Silicon. The target device is a fully planar monolithic Schottky diode working at terahertz frequencies which can be fabricated in arrays on a semiconductor wafer for imaging applications.

A measure of the quality of a radiation detector is its noise equivalent power (NEP). The noise power of a real Schottky diode is hard to predict, as it is the sum of several contributions (recombination current, Johnson noise, 1/f noise) which in turn depend on the signal read-out frequency. Therefore, we only performed calculations of the voltage responsivity β_V with a simplified diode model [4], which includes its series resistance Rs, its junction resistance Rj, and its junction capacitance Cj. The latter two quantities were derived from the junction dimensions by geometrical calculations.

The plot shown in Fig. 38.1 summarizes the results of the calculations, and clearly shows that sub-micrometric areas are necessary to reach terahertz frequencies. Junction with these dimensions cannot be produced with conventional optical lithography. This is the reason why we had to implement in the present Schottky diode fabrication process the “T-gate” technology based on electron beam lithography used for high electron mobility transistors.

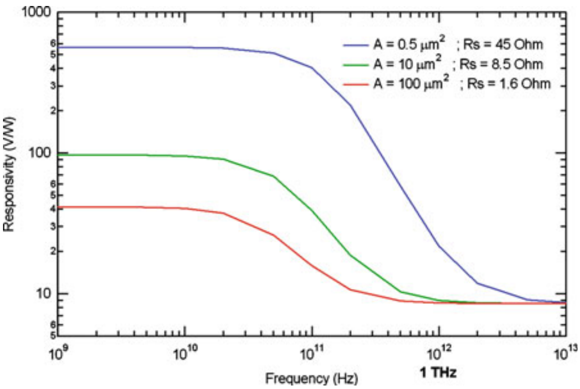

Fig. 38.1 Calculated responsivity of a Schottky diode detector as a function of diode parameters

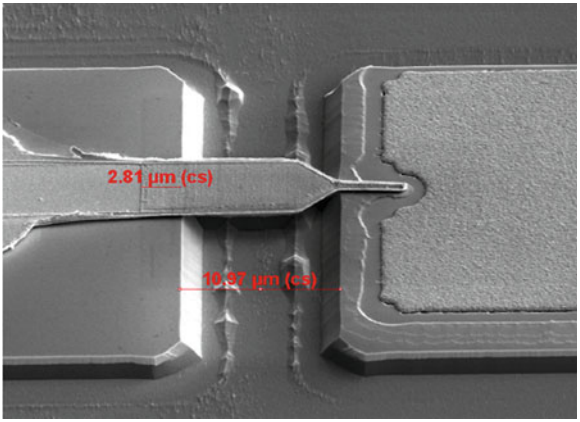

Fig. 38.2 SEM image of a terahertz Schottky diode fabricated at IFN-CNR

38.3 Diode Fabrication

Monolithic arrays of Schottky diodes are fabricated on a GaAs wafer with a layer structure on top. On the GaAs semi-insulating substrate, a 1-micron thick n^+-doped ($n_D = 5 \times 10^{18}$ cm^{-3}) and a 0.1-micron thick n-doped ($n_D = 1 \times 10^{18}$ cm^{-3}) GaAs layers have been sequentially grown by Molecular Beam Epitaxy. The device layout is based on two rectangular mesas of 30 × 150 microns separated by a 10-micron gap, which actually form a dipolar antenna tuned at 220 GHz. A Ge/Au/Ni metallization followed by annealing at 405°C on the n^+-doped layer is used for the ohmic contact to the cathode (semiconductor side of the junction). An evaporated Ti/Au bilayer on the n-doped GaAs forms the anode (metal side of the junction) with the following special layout obtained by electron-beam lithography on a trilayer resist structure: a large contact pad on the first mesa, a micrometric air-bridge between the mesas and a sub-micron finger with a "T-gate" profile displaying a 1 micron wide "head" and a footprint of 200 nm (see Fig. 38.2). The "T-gate" profile allows a small Schottky junction area, however not affecting too

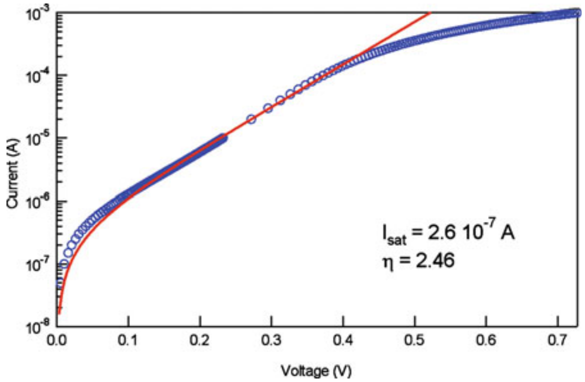

Fig. 38.3 DC *I–V* characteristics of a typical diode displaying pure exponential behaviour (*continuous line*) over two decades in current

much the contribution to the series resistance and inductance due to the anode metal finger. After the two metallization steps, a wet mesa-etching step is performed to isolate the anode and cathode contact pads. Also, at the mesa etching step the air-bridge is formed, and this eliminates the parasitic capacitance associated with the anode contact pad.

38.4 *I–V* Characterization

After device fabrication, selected diodes were wire-bonded and mounted in a package for dc characterization. The forward-bias *I–V* characteristics of the diode are shown in Fig. 38.3. To fit the data we used the classical Schottky model:

$$I(V) = I_{\text{sat}}(\exp(q(V - IRs)/\eta k_B T) - 1)$$

where I_{sat} is the saturation current, η is the ideality factor, Rs is the series resistance and q is the electron charge. The continuous line is a fit to the classical Schottky model with saturation current and ideality factor values reported in the plot. The deviation from the fit above 10^{-4} A is to be attributed to the voltage dependence of $\eta\tau$ and therefore data above $V = 0.4$ V are disregarded in the fit. A series resistance $R_s = 150 \pm 50\ \Omega$ is extracted from the fit (the uncertainty being related to assumptions on the ideality of the junction [5]). The junction capacitance C_j is estimated from geometrical calculations to be 5×10^{-15} F, with a resulting cutoff frequency $f_c = 1/2\pi R_s C_j = 210 \pm 60$ GHz. Efforts are ongoing to improve the junction ideality by surface treatment prior to anode metal deposition and to decrease R_s by Ohmic contact optimization.

38.5 Conclusions

In this work we presented the design, fabrication and dc characterization of Schottky diodes with cutoff frequency in the terahertz range. The devices were designed to operate as direct detectors of terahertz radiation and fabricated in monolithic arrays for imaging applications.

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