Fabrication and Characterization of Quasi-Optical Terahertz Nanorectifiers with Integrated Antennas

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Abstract. We are developing microelectronic terahertz rectifiers by scaling down the dimensions of GaAs Schottky diodes and field-effect transistors to the sub-micron range, and by investigating the effect of on-chip parasitic capacitances on the square-law power detection signal. For broadband operation at THz frequencies the terahertz oscillating signal is fed to the device by integrated lithographic planar antennas, suitably coupled to a silicon substrate lens. Such room-temperature THz detectors can be fabricated in arrays and naturally provide picosecond response time, suitable for detection of coherent THz radiation produced by single electron bunches in accelerators.

1. Introduction

Microelectronic rectifiers based on Schottky diodes and Field-effect transistors (FET) fabricated on epitaxial layers of III-V semiconductors like GaAs are commonly employed as square-law power detectors in millimeter wave integrated circuits (MMICs) working up to 100 GHz [1]. While terahertz Schottky diodes have been developed for mixing applications, it was recently demonstrated that FETs can be employed as terahertz detectors as well [2]. The working principle is based on the assumption that the non-linearity of current-voltage (I-V) characteristics exploited for diode and transistor operation at dc-to-gigahertz frequencies is somehow preserved in the sub-millimeter waves, where the concepts of power coupling and transit time delay are more properly used instead of simple I-V curves. In classical models [3] the square-law responsivity is directly proportional to the second derivative of the I-V curve, and inversely proportional to the dynamic resistance of the device (the inverse first derivative of the I-V curve). For these reasons, a good rectifier should display both highly nonlinear characteristics and low resistance at the bias point.

In this work, we demonstrate that by scaling the device size down to the nanometric range and by decreasing and properly controlling the on-chip parasitic capacitances, it is possible to preserve the rectifying behaviour of MMIC technology workhorses such as GaAs Schottky diodes and InGaAs/AlGaAs field-effect transistors up to 1 THz at least. For broadband detector operation at THz frequencies, the oscillating signal cannot be easily fed to the nanodevice by usual integrated microstrip or coplanar waveguides. Here, we fabricated the devices together with integrated lithographic planar antennas. The planar antenna can be suitably coupled to a silicon substrate lens pressed on the
backside of the GaAs chip, and works as an optical-to-electronic converter: a free-space terahertz radiation beam, like that emitted by electron bunches in a synchrotron radiation beamline, is focused on the antenna by the silicon lens and the oscillating electric field is converted into a terahertz oscillating current, flowing through the active device [4,5]. The responsivity of terahertz microelectronic detectors, also called quasi-optical rectifiers, mostly depend on the efficiency of such optical-to-electronic conversion, which is related to impedance matching issues, parasitic and intrinsic LC resonances and Gaussian beam quality [4].

We design the diodes and transistors with integrated antennas for terahertz operation and we fabricated them in our clean room with lithographic processes similar to those normally used by the microwave industry. The device quality and the process yield and reproducibility are not optimized, as our aim is rather the experimental investigation of the optical-to-electronic conversion. Selected devices with best dc characteristics are mounted in home-made packages with silicon lenses and we measured their responsivity in the 0.2-0.7 THz range with a tunable sub-millimeter electronic oscillator coupled to free space by a horn antenna.

At present, typical responsivities of quasi-optical rectifiers lie in the range 1-100 V/W, with a noise equivalent power around 1 nW/Hz which can be favorably compared to that of classical room-temperature terahertz detectors such as pyroelectrics and Golay cells. As an advantage, quasi-optical rectifiers could be fabricated into arrays for beam-scan and beam-profiling, and naturally provide response time in the picosecond range (actually, as fast as the readout circuit allows), which is ideal for the detection of short THz radiation pulses produced by single electron bunches in accelerators [5].

**Figure 1.** Scanning Electron Microscope image of an integrated log-periodic antenna fabricated by electron-beam lithography in the CNR-IFN clean room. The nominal antenna bandwidth is 0.1-1.0 THz, as the teeth radius ranges from 350 to 35 microns. At the antenna feed, either an air-bridge Au/Ti/n-GaAs Schottky diode (upper right inset) or a high-electron-mobility transistor with pseudomorphic InGaAs channel (lower left inset) are fabricated. In the case of the transistor, the gate electrode is added in a subsequent step (not shown).
2. Design and Fabrication of Schottky Diode Rectifiers

The Schottky diode based on epitaxial electron-doped gallium arsenide (n-GaAs) is probably the most important microelectronic device for operation in the sub-millimeter and terahertz range [1]. Diode areas of the order of 1 square micron are needed to obtain a low junction capacitance $C_j \sim 10^{-15} \text{F}$, which was classically achieved by pressing etched tungsten whiskers on GaAs chips [3]. In the last decade, air-bridge lithographic anodes have been developed (see Fig. 2A), allowing for multiple anodes on–chip, higher yield of the fabrication process, and studies of the physical properties of the Schottky junction at terahertz frequencies. The prominent role played by epitaxial n-GaAs diodes in sophisticated terahertz spectroscopic instruments such as heterodyne mixers [1,4,5] and frequency multiplied oscillators is due to the simultaneously high electron mobility and density (up to 3000 cm$^2$/Vs and $5 \times 10^{18}$ cm$^{-3}$ at room temperature, respectively) obtainable in GaAs, which ultimately provide a low series resistance $R_s$ and hence a high cutoff frequency $f_c = 1/2\pi R_s C_j$. More recently, the development of terahertz imaging and telecommunications points towards the development of fast terahertz power detectors, producing a rectified signal modulated up to the nanosecond range [5].

We are developing Schottky diodes with high doping level of the semiconductor ($N_d > 10^{18}$ cm$^{-3}$) for operation at THz frequencies. The high doping is crucial for very high frequency operation, since it provides a small series resistance and a short dielectric relaxation time [6]. However, in highly doped metal-semiconductor junctions the tunneling current through the quasi-triangular potential barrier contributes substantially to the total current, even at room temperature [7]. This is shown in Fig. 2 where we performed the calculation of the potential barrier seen by electrons in the semiconductor (Fig. 2a) and of the tunneling coefficient $T(\epsilon)$ as a function of the distance in energy $\epsilon$ from the top of the barrier by using the triangular-barrier approximation (Fig. 2b). Temperature was set to 295 K and standard Fermi distribution functions were employed for the metal (Au) and the semiconductor (GaAs). The doping level of GaAs was varied from $N_d = 10^{17}$ cm$^{-3}$ which is normally used for microwave rectifiers and displays negligible tunneling contribution (dashed lines in Fig. 2) to $N_d = 3 \times 10^{18}$ cm$^{-3}$ which is at the verge of the transition to a completely symmetric low resistance junction (i.e. an Ohmic contact to the semiconductor, thick lines in Fig 2) and hence cannot be used as rectifier. Our choice of the doping level for the GaAs epitaxial material was therefore $N_d = 1 \times 10^{18}$ cm$^{-3}$.

![Figure 2](image.png)

**Figure 2.** (a) Potential barrier seen by electrons in GaAs as a function of the distance from the Au/GaAs Schottky junction. (b) Differential tunnelling coefficient as a function of energy distance from the top of the barrier (abscissa and ordinate axis are reversed on purpose). The triangular-barrier approximation is used for the calculation in (b).
The typical signature of tunneling contribution in the I-V characteristics shown in Fig. 3 for our and other Schottky diodes is an ideality factor \( \eta \) different from unity. Indeed, in forward-bias the tunneling current \( I_{\text{tun}} \) has the same exponential dependence on the bias voltage \( V_b \) as the thermionic current \( I_{\text{th}} = I_{\text{sat}} \cdot \exp(V_b/kT) \), because tunneling essentially takes place close to the top of the barrier, where the value of the Fermi distribution in the semiconductor \( F_s \ll 1 \) can be approximated by \( F_s = \exp[(V_b-\phi_b)/kT] \), and \( I_{\text{tun}} = T_e \cdot \exp(-\phi_b/kT) \cdot \exp(V_b/kT) \) where \( T_e \) is the tunneling probability integrated from the top of the barrier to a given value \( \varepsilon \) and \( \phi_b \) is the barrier height (0.85 V in Au/n-GaAs). The total current can then be expressed in the usual compact form

\[
I = I_{\text{th}} + I_{\text{tun}} = I_{\text{sat}} \cdot \left[ \exp(V_b/\eta kT) - 1 \right]
\]

which defines the ideality factor \( \eta \). Therefore, the main effect of the tunneling current is a modification of the exponential characteristic voltage, conventionally expressed in terms of \( \eta > 1 \). The I-V plot of our standard diodes in the forward-bias region (Fig. 2b, \( V_b > 0.4 \)) indeed shows an exponential dependence with \( \eta = 1.7 \) and a saturation current much larger than that of diodes of equal area fabricated on GaAs epilayers with \( N_d = 10^{17} \text{ cm}^{-3} \) [5], hence confirming that tunneling plays a key role in our devices and that classical Schottky theory (Eq. 1) describes well the I-V curve of our standard diodes.

Let us now focus on the I-V curves of Fig. 3b close to zero bias. I-V measurements were performed with a dc-current bias, which is the configuration used to bias rectifying detectors. In the case of the standard diode, the minimum bias current \( I = 100 \text{ nA} \) corresponds to \( V_b = 0.37 \text{ V} \), as no such current can flow in the diode without a significant applied voltage. Recently, we have also successfully fabricated Zero Bias Diodes (ZBD) with a very similar process where we have additionally shaped the three-
dimensional junction geometry to further decrease the Schottky barrier width [9]. In these diodes, the minimum bias current flows for \( V_b < 10 \text{ mV} \), displaying quasi-ohmic I-V relation around the zero-bias point, not described by Eq. 1. From now on, we shall define the dynamic junction resistance, mainly due to tunneling, at the bias point

\[
R_d = (dI/dV)^{-1} @ V_b
\]  

(2)

by keeping in mind that the I-V curves are still non-linear at any \( V_b \), including \( V_b = 0 \); this is of course crucial for the intended use of the diode as THz radiation rectifier. Together with the \( R_s \) and \( C_j \), \( R_d \) defines the zero-bias cutoff frequency of the rectifier \( f_{ci} \), which is derived by calculating the transfer of power from the diode to an external load equal to \( R_d \):

\[
f_{ci} = 1/2\pi C_j (R_s R_d)^{0.5}
\]  

(3)

If we take \( R_s \approx 20 \text{ Ohm} \) (a typical value for highly doped epitaxial n-GaAs diodes) and \( C_j = 1 \text{ fF} \), zero-bias rectification at THz frequencies requires \( R_d \) as low as possible. As seen from Fig. 3, for standard diodes with sub-micron area, \( R_d > 10^9 \text{ Ohm} \) at zero bias, therefore the diode needs to be forward-biased to work as THz detector. Instead, for the ZBDs we obtain minimum values for \( R_d \) around 100 \text{ kOhm} for 0.4 \text{ um}^2 diodes at \( V_b = 0 \) which indeed allow for THz detector operation without any applied dc bias [9], a clear advantage for future multi-pixel arrays.

In summary, tunnelling currents through a Schottky junction realized on a highly doped GaAs layer provide low dynamic resistance as shown in Fig. 4a, by still keeping a nonlinear dependence of the tunnelling coefficient as shown in Fig. 4b for a realistic value of the peak-to-peak THz voltage applied to the diode through a planar antenna in quasi-optical mode.

![Figure 4](image)

**Figure 4.** (A) Tunneling current (Eq. 1) in a 0.2x2 \text{ µm}^2 Schottky junction calculated in the triangular-barrier approximation, as a function of the constant electric field in the depletion region. Note the exponential dependence on the electric field. (B) Tunneling probability \( T_e \) integrated over the Schottky barrier for a Au/GaAs junction with high doping level of \( N_d = 10^{18} \text{ cm}^{-3} \) as a function of a small applied voltage \( V_{THz} \) of magnitude comparable to that produced by realistic terahertz beam (c.w. power of 1 mW and diffraction-limited focussing are assumed). Note the dependence of the tunnelling probability on \( V_{THz} \) which ensures partial rectification at zero dc bias.

We designed the n/n+ epitaxial structure according to calculations shown in Fig. 2 (100 nm with \( N_d = 1\cdot10^{18} \text{ cm}^{-3} \) on top of 1000 nm with \( N_i = 5\cdot10^{18} \text{ cm}^{-3} \) for ohmic contact to the cathode). Layers were grown by Molecular Beam Epitaxy on a semi-insulating GaAs wafer. On these wafers, we have fabricated antenna-coupled terahertz Schottky diodes in our clean room. As shown in the scanning-electron micrograph of Fig. 3a, the sub-micrometric Schottky junction is achieved by contacting the GaAs surface with the extremity of a free-standing metal bridge, with mesa isolation between anode and cathode pads to cut parasitic capacitances. The layout of the alloyed ohmic contacts was identical in both cases, and it was designed to work as an integrated planar dipole antenna, centered at 0.22
THz. The sub-micron metal-semiconductor junction was realized with the help of an electron-beam writer, by patterning rectangles at different doses on a trilayer resist polymer based on polymethylmethacrilate (PMMA), so to obtain a “T-section” anode [9] with lateral footprint of only 0.2 microns, while the anode length (2 to 10 µm) was designed to obtain diodes of different area (0.4 to 2 µm²). After patterning, in standard diodes surface oxides are first removed by immersion of the wafer in a NH₄OH solution and then the metal contact is evaporated (30 nm Ti and 400 nm Au). After the mesa-etching step, which also suspends the air-bridge, wafers are dc-tested before dicing.

3. Terahertz Rectification Measurements
Terahertz rectification measurements took place at University of Rome “Sapienza” by using the radiation source therein installed in the framework of the SPARC linear accelerator project. The devices are diced in 3x3 mm chips, containing many diodes, whose polished backside is put in contact with the flat side of a hyper-hemispherical Silicon lens, which focuses an incoming radiation beam onto the diode. The contacts work as a λ/2 dipolar antenna resonating at 0.25 THz. The distance between two neighboring devices is only 320 µm, which allows the chip to be mounted in the focus of a single Si substrate lens (the effective wavelength λ_eff = 450 µm defines the focal spot size in case of ideal diffraction-limited focussing). For responsivity measurements at 0.27 THz we have used the quasi-optical setup shown in Fig. 5, based on a Gunn oscillator followed by a frequency multiplier (270GHz-Tx by Virginia Diodes Inc.) and by a horn antenna. The continuous-wave beam at 0.27 THz is mechanically chopped at 330 Hz and sent to the silicon lens. The detector box contains an analog video amplifier with bandwidth of 1 kHz and gain of 1000, ac-coupled and directly bonded to the diode chip, together with a bias-tee which allows dc-bias by batteries, adjustable with a potentiometer. In this way, the pick-up of ambient noise can be neglected and the signal can be safely input in a standard lock-in amplifier.

![Figure 5. Compact terahertz generator installed at University of Rome “Sapienza” used for rectification measurements on Schottky diodes and calibration of other detectors. Radiation at 0.27 THz is emitted by a Gunn diode at 90 GHz followed by a frequency tripler (by Virginia Diodes Inc.) and by a horn antenna. The continuous-wave beam at 0.27 THz is mechanically chopped at 330 Hz and sent to the silicon lens. The detector box contains an analog video amplifier with bandwidth of 1 kHz and gain of 1000, ac-coupled and directly bonded to the diode chip, together with a bias-tee which allows dc-bias by batteries, adjustable with a potentiometer. In this way, the pick-up of ambient noise can be neglected and the signal can be safely input in a standard lock-in amplifier.](image)

The diode responsivity is calculated by dividing the lock-in signal by the video amplifier gain and by the radiation power reaching the diode, estimated around 0.01 mW by calculating the solid angle overlap between the horn antenna and the silicon lens patterns. The results are shown in Fig. 6 and display a very good agreement with the theoretical responsivity calculated from the measured non-
linearity of the dc characteristics. The responsivity was found to be independent from the chopper frequency in the 10 Hz – 550 Hz range.

![Graph showing responsivity vs. voltage](image)

**Figure 6.** Terahertz responsivity of a GaAs Schottky Diode with junction area of 2 square microns, produced at CNR-IFN and measured at University of Rome “Sapienza” as a function of $V_b$. Red circles: rectified signal when the packaged diode is exposed to 0.27 THz radiation. Note that the diode cutoff frequency according to Eq. 3 is 1.1 THz. Green line: response calculated from the I-V curve (blue line, right axis) in Fig. 3 following the model of Ref. 3. The agreement is very good, apart from the nonzero response signal found at zero bias, which is due to asymmetric tunnelling (see Fig. 4 and related discussion).

4. **Heterostructure Field Effect Transistor Rectifiers**

InGaAs-channel HFETs with gate length of 1 micron and channel width of 10 microns were fabricated with integrated bow-tie antennas (Fig.1). For the device described in this paper, the antenna couples the radiation polarized parallel to the channel direction to the carriers in the two-dimensional electron gas (2DEG). Out-of-phase self-mixing with the gate voltage (possibly induced by capacitive coupling among contact pads and/or the gate electrode itself) produces the rectification of the source-drain current inside the channel, and a down-converted output can be measured at low-frequency at the drain port. Details of the mixing mechanism, including the role of collective (plasma) oscillations have been discussed in several works [2, 10].

![Heterostructure Field Effect Transistor Detector](image)

**Figure 8.** Heterostructure Field Effect Transistor Detector mounted in a Quasi-optical package for terahertz rectification measurements developed at CNR-IFN. The Detector has two SMA bias/readout ports (gate and drain contacts) and the radiation is coupled through a hyper-hemispherical silicon lens (at the center of the white Teflon spring) and an on-chip planar lithographic antenna (see Fig. 1).
In the present device, we made an effort to optimize the HFET detector sensitivity by setting the maximum responsivity close to zero gate bias \( V_g \). In Fig. 7 we show the transfer characteristics of the transistor (drain current at fixed drain voltage bias \( I_d \) vs. \( V_g \)) displaying a threshold voltage of \( V_{th} = -200 \) mV. This means that the 2DEG in the channel is partially depleted at \( V_g = 0 \) and therefore strongly non-linear \( I_d-V_g \) characteristics are expected also at THz frequencies with no dc bias applied at the gate. This simplifies the detector circuit, in a way similar to what happens in the ZBD Schottky detectors of section 2 [9].

To measure the value of the rectified signal, the HFET chip was packaged together with a silicon lens and it was exposed to the radiation generated by a frequency-multiplied tunable electronic oscillator in the range 0.15-0.75 THz (by Virginia Diodes Inc.), emitted in free-space by a horn antenna, collected and refocused onto the detector lens by a pair of 90° off-axis parabolic mirrors. The emitted power was independently measured by a calorimeter to account for variation of the emitted power with frequency. The oscillator output is amplitude-modulated at 1 kHz by a master oscillator, which also works as reference for a lock-in amplifier attached to the drain port to measure the response signal.

Full spectroscopic characterization will be reported elsewhere [11]. As an example, we show in Fig. 8 the dependence of the response signal of one of the fabricated HFET to radiation at 510 GHz as a function of \( V_g \). The peak responsivity value is found at the pinch-off voltage, as described in Ref. 2 and as expected from the higher nonlinear coefficient in that voltage range. As seen from the red curve, the result of our design and fabrication efforts is that almost 60% of the maximum response signal is obtained at \( V_g = 0 \). A quantitative comparison of noise and responsivity of Schottky and HFET detectors is ongoing [10].

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