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Terahertz Rectifyier for Integrated Image Detector

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Abstract

We present a new CMOS compatible direct conversion terahertz detector operating at room temperature. The rectenna consists in a truncated conical helix extruded from a planar spiral and connected to a nanometric metallic whisker at one of its edges. The whisker reaches the semiconductor substrate that constitutes the antenna ground plane. The rectifying device can be obtained introducing some simple modifications of the charge storage well in conventional CMOS APS devices, making the proposed solution easy to integrate with existing imaging systems. No need of scaling toward very scaled and costly technological node is required, since the CMOS only provides the necessary integrated readout electronics. On-wafer measurements of RF characteristics of the designed rectifying junction are reported and discussed.

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Keywords: Image detector; THz antennas; rectifying antenna (rectenna); double barrier junction.

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1. Introduction

THz imaging and spectroscopy applications have a great potential in time-domain spectroscopy [1], communications [2], security control [3], and biomedical imaging [4]. For this reason in past decades a great interest of the research community has been attracted by this region of the electromagnetic spectrum, pushing the microwave and optical THz devices through a constant progress in the development and the improvement of detectors in terms of noise equivalent power.

Currently the main interest is the development of low cost, fast, highly sensitive, compact and room temperature THz detectors. The feasibility of rectifying antennas (rectennas) for the detection of freely propagating THz radiation has been demonstrated [5]. The radiative part of these devices is typically formed by an antenna that focuses the energy of the impinging electromagnetic field into a localized spot called active region, where the rectifying element is placed. The latter produces a continuous current proportional to the energy of the impinging electromagnetic wave.

Recently we presented a new structure resulting from the integration of a 3D antenna with widely produced commercial CMOS image detector [6]. The fabrication process, described in [7], permits to integrate the three dimensional antenna directly on the surface of the chip, by means of MEMS technology, and ensures a very low parasitic capacitance, because of the distance between antenna spires and the chip surface.

A further step of the development of this THz technology is the development of low cost, fast, highly sensitive, compact and room temperature detectors. The integration in arrays, in standard CMOS technology, is also mandatory to make exploitable

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readout and elaboration electronics capabilities. This paper presents a new approach resulting from the direct integration of the antenna with a rectifying device obtained by modification of commercial CMOS Image Sensors (CMOS ISs) [8].

Nowadays CMOS Image Sensors (CMOS ISs) are predominant electronic devices in the field of digital imaging[9]. The photosensitive element of the pixel is the pinned photodiode, i.e. a p-n-p structure constituting the charge storage well (SW) dedicated to the photocurrent integration during the exposure time. In the readout cycle the integrated charge is transferred to a capacitance (“floating diffusion”, FD) inducing a voltage difference that is sampled with a transistor in source follower configuration. The complete charge transfer from photodiode to the floating diffusion allows the elimination of the thermal reset noise of the capacitor, referred as kTC noise, by means of the correlated double sampling. This property in combination with the extremely low dark current produced by pinned photodiode contributes to the high image quality of CMOS ISs.

The semiconductor structure implemented in the detector is suitable to perform the rectification of terahertz radiation and to permit accumulation of the rectified charge into a storage capacitance and its readout, by means of a technology compatible with CMOS ISs. The rectifying device with vertical extension of few tenths of nanometers can be created at the base of the nano-whisker previously described, using one of its metal edges as part of the electronic device itself.

This work is organized as follows. In section 2, the structure of the detector is presented and its principle of operation is discussed. Section 3 is dedicated to the presentation of a test structure of the rectifying device and to the characterization of its performance. The effect of doping distribution due to different implantation processes is presented.

2. The rectifying device

In Fig. 1. (a) the structure of the rectenna and its connection with the photodetector is presented. The structure is designed as a combination of an antenna fabricated on the surface of the chip with a rectifying junction capable to produce the direct conversion of terahertz electromagnetic field into DC current [10]. Different semiconductor devices can be used for this purpose, e.g. Schottky diodes, MIM diodes, low barrier junctions. Nevertheless, the necessity to adopt an approach as close as possible to the technology of CMOS photodetectors, induces to use a metal/oxide/semiconductor (MIS) structure as it may take the advantage of gate oxide already present in the detector structure. The rectifying structure presented here is realized by a double barrier formed by the metal of the whisker, chosen with working function similar to an n+ doped semiconductor, a p+ doped surface layer and by the semiconductor storage well.

A p+-type implanted surface layer is commonly used in CMOS image detectors to separate the weakly n--type doped portion of SW from the semiconductor surface [9].

In the double barrier structure a rectifying effect arises from the different extension of two depletion regions, very short for the first junction between the metal and the p+ layer, much more extended for the second junction, between the p+ layer and the SW. The rectifying effect can be explained as follows: the electric field variations induced by the antenna and focused by the whisker on the rectifying device, induce variations of voltage drop through the depleted zones of the two barriers. The majority of the voltage drop occurs through the second depletion region, mainly extending into n- Si of the SW, much wider that the short depletion region, related to the “first junction”. As a consequence, with positive voltage applied to the metal, a reduction of the barrier of the “second junction” occurs, and electrons preliminarily stored in the SW can be extracted. On the contrary, with negative voltage, electrons present in the metal layer are injected in a much lower number into SW, since the barrier of the “first junction” is reduced by a much smaller amount due to its shorter extension.

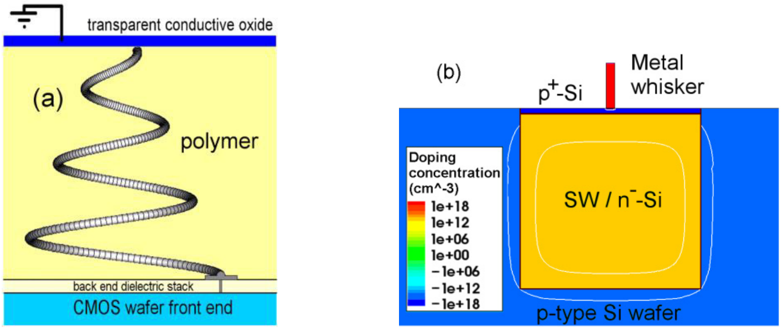

Fig. 1. (a) Schematics of rectenna geometry; (b) front view of the metallic whisker facing the storage well.

Numerical simulations of the semiconductor device were performed by means of Synopsis Sentaurus TCAD tools. Simulator engine allows to perform 2.5D simulations setting to 100nm×100nm the area of the metal contact. As reference, these contact dimensions are achievable by means of 193nm ArF DUV photolithography process.

Since the structure is supposed to be zero-biased, the barrier must be sufficiently low (0.3–0.5eV) in order to produce an appreciable rectified current, even under presumably low voltage variations induced by the THz radiation. Fig. 2 reports the 2D distribution of the barrier beside the 5ectifying device.

The use of a not so scaled CMOS technology is not a limiting factor. In fact, simulations results [11] demonstrate that these dimensions are suitable to achieve a very high FE, and that a further reduction would bring no substantial advantage.

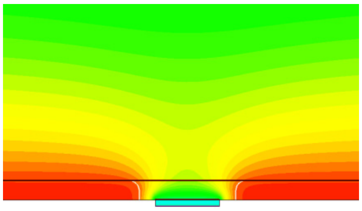

Fig. 2. 2D plot of conduction band energy inside the storage well calculated in equilibrium with the titanium metallic.

3. On-wafer measurements

We developed a test structure to verify the rectification properties of the detector. The test structure reported in Figure 3 does not include the antenna and is designed for tests at frequencies well below THz range, in order to be handled with standard probes and available instrumentation. The signal is applied by a radio frequency generator to emulate the excitation coming from the receiving antenna. This latter measurement setup choice may appear somewhat arbitrary, however in the following we will show that it is still possible to provide expected results at THz range coherent with real measures at lower frequencies.

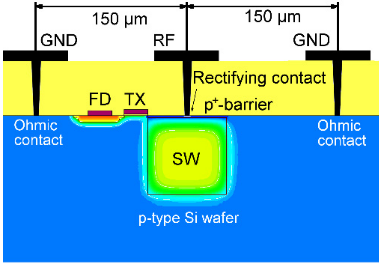

Fig. 3. A schematic description of the test structure. Dimensions of the RF pads and of SW are not in scale.

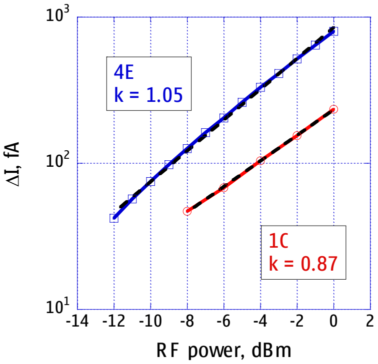

Fig. 4. Rectified current versus applied power for the two structures 4E and 1C.

Table 1. Implantation scheme.

Group	**Energy keV**	**Dose cm^{-2}**
1C	13.5	1.E13
4E	5.0	5.E13

The test structure is realized with minor changes from a standard configuration of a CMOS photo-detector using the Aptina/ON Semiconductor 0.15μm technology node. The additional step consists in an extra p-type doping implantation below the whisker in order to trim the barrier height. Such implantation can be performed through a properly designed window through which also the metal used for the realization of contact, Ti, is deposited. Further metal deposition is performed to obtain a via hole between the pad metallization and the rectifying contact.

Finally, at top metallization level, three pads are realized with sizing suitable to be contacted by RF microprobes. In particular, Cascade ACP-150 GSG microprobes were used during measurements. The two external ground pads are electrically connected to the p+-Si layer, and to the doped substrate surrounding the SW, by means of via holes and ohmic contacts.

In order to test the rectification model, and to evaluate the rectifying efficiency, we performed measurement at 40 GHz on two samples with different parameters of the *p*-type doping implantation. In particular sample 4E had an higher dose and lower energy with respect to sample 1C, as reported by Table 1.

Fig. 4 reports the rectified current measured by pico-ammeter versus the RF power applied to the signal pad. The voltage levels at the gate of TX was 4V for both curves.

A linear approximation of curves in Fig. 4 can be used to evaluate the detector efficiency. We approximate as linear the relationship between the RF power expressed in dBm, P_{dBm}, and ten times the logarithm of the current, I_{dBA}, as given by

$$P_{dBm} = P_{dBm,0} + k\left(I_{dBA} - I_{dBA,0}\right), \tag{1}$$

where $P_{dBm,0}$, $I_{dBA,0}$, and the coefficient k can be calculated from geometrical regression of measured data. This approach allows to account eventual nonlinearities in the rectification. From the sample 4E we obtained k=1.02, while for the sample 1C the coefficient resulted in k=0.84. This effect can be explained as due to the much steeper and superficial distribution of the dopant in sample 4E, with respect to sample 1C. In this condition the rectification effect of the double barrier structure is enhanced, giving rise either to larger values of rectified current, and of the nonlinearity coefficient. This effect overcomes the increase of the barrier height expected due to the increased doping dose.

Numerical simulations of the semiconductor device, performed by means of Synopsis Sentaurus TCAD, showed that the rectification process, experimentally verified at 40 GHz, is also effective up to 1THz. One pole behavior, with a cut-off frequency of 120GHz, can be identified leading to the evaluation of NEP at 1 THz of $51.\ 10^{-12} W/\sqrt{Hz}$.

4. Conclusions

In this paper a new THz radiation detector operating at room-temperature, compatible direct conversion in CMOS ISs, is presented and experimentally evaluated. We demonstrate that a modification of a limited region of the surface of the CMOS ISs pixel, placed in contact with the metallic antenna pad, provides an efficient rectifying device. The antenna and the rectifying device, i.e. the rectenna structure, exposed to electromagnetic radiation gives rise to charge injection into the storage well of APS device that is collected by the readout electronics. We presented measurements at a frequency of 40 MHz which demonstrate the effectiveness of the rectifying devices, which confirm the rectification effect due to the formation of a double barrier just below the antenna whisker. The experimental results, supported by 2D numerical simulations, permit an evaluation of the NEP at 1 THz.

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