Increasing responsivity of THz Radiation Detector Based on MOSFETs

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Abstract— Approaches based on thinning down the substrate under the antenna are often used in order to increase efficiency of detectors built with MOSFETs and antennae printed on thick substrates. Such detectors have relatively low responsivity. In applications where cheap individual pixels are required, standard silicon lenses used to increase the responsivity are prohibitively expensive. In this paper an alternative approach based on a CNC-milled parabolic mirror integrated in the package of the detecting chip is described and compared with results obtained with plastic lenses installed in front of the detector.

I. INTRODUCTION

In the literature dedicated to detection of the THz radiation one often finds references to circuits based on small-scale Shottky diodes [1] and HEMT transistors [2]. For several years metal-oxide-semiconductor field-effect transistors (MOSFETs) have also been used in this role [3], which allows use of relatively cheap silicon-based technology readily available through multiple foundries in the world. All such detectors are typically integrated monolithically with antennae fabricated in one of the metallization layers [3].

Placing the antennae on thick dielectric substrate introduces substrate modes which diminish responsivity of the structure. In order to reduce this effect often a silicon lens is attached to the substrate [4], or the substrate thickness under the patch antenna is decreased with proper use of multiple metallization layers [2], thinning-down the original substrate or introducing thick photoresist layers (e.g. made of SU-8 material) and insulating the antenna from the original substrate [3].

While silicon lenses guarantee broadband operation of the detector and the overall responsivity, they are also expensive. Approaches based on thinning the substrate are cheaper, since they can be integrated into standard manufacturing processes. They also typically lead to obtaining detectors sensitive to narrow frequency bands, which opens possibilities of applying the MOSFET-based detecting technology in cheap spectrometry solutions or “multi-color” imaging. However, a disadvantage of such narrow-band structures is their low responsivity. In this paper a comparison of two relatively cheap methods of increasing the responsivity of such detectors is presented.

II. TWO METHODS OF INCREASING RESPONSIVITY

As shown in [5] the directivity and radiation efficiency of detector’s antenna may affect its responsivity. In order to improve it, the directivity must be increased without affecting radiation efficiency. One way of achieving this goal is to apply a cheap lens made of plastic (relatively low dielectric constant and low-loss material). The lens mounted in front of the detector increases the aperture of its antenna and concentrates the incoming wave’s energy at the antenna integrated with the MOSFET.

The other method is based on integration of a parabolic (or a semi-parabolic) mirror in the package of the detector. The mirror is CNC-milled in a brass (or aluminum) block that plays also a role of a rigid support for the detector chip. The chip itself is installed on a dielectric plate mounted at the rim of the concave mirror, and faces downward to its bottom. The dielectric plate holds the chip in place but also allows routing thin tracks needed to bias the MOSFET and sense the photo-detection signal. The depth of the mirror is selected so that the detector chip is suspended in the vicinity of the focal point of the mirror in a location that minimizes the spill-over and illumination losses [7]. With careful choice of the parameters of the shape of the mirror (its diameter, focal distance and milling depth), this approach does not need any additional support structure that increase the profile of the complete detector, which is the case when add-on lens is employed. Although in both approaches the distance between the detector chip and the mirror or lens is similar, in case of the lens-based system one needs also to account for the height of the chip’s package. No additional package is needed in the mirror-based method.

Both methods keep properties of the original detecting structure in terms of narrow-band operation. However, in each case the optical path (either the lens or the parabolic reflector) is broadband. Thus, sensitivity to different frequency band can be obtained by replacing the original detector chip and not the lens or the mirror. This may be of importance in spectrometry applications, where several narrow bands must be analyzed in a short sequence.

III. MEASUREMENTS

The proposed methods were tested by means of measuring the responsivity of an example sub-THz detector. The detector chip of dimensions 2.70×2.55×0.40 mm³ contains a MOSFET (with channel dimensions of 5×10 μm²) integrated with an array of rectangular patch antennas fabricated on a locally tinned-down silicon substrate as described in [3]. After the responsivity of the detector alone was measured, the plastic lens (or the mirror) was added and the responsivity measurements were repeated. In this way the same detector chip was used in all measurements, which allowed accurate estimation of the responsivity improvement for each of the methods without the need to account for chip-to-chip parameter variation.

The measurement a set-up consisted of the 340 GHz Transmitter (Tx340) from VDI, Inc. The Tx340 system provides as much as approx. 20 mW of power monochromatic incident wave of frequency that is selectable in the band of
315 – 355 GHz with a resolution much better than 1 GHz. The DC photo-detection signal was filtered out using a lock-in amplifier and measured. During the measurements the detector and the lens (or the mirror) were mounted on a XYZ stage, which allows positioning of the sample which is particularly of importance in case of measurements of lens-based systems.

Several responsivity measurements were performed. First, the responsivity of the detector installed on a ceramic dual-in-line (DIL) package was measured. Then the plastic lens of diameter approx. 10 mm described in [7] was added in front of the package and the responsivity of such a detecting system was measured again for various distances between the detector and the lens. While shifting the detector away from the lens, care was taken to keep the detector on the lens’ axis.

The mirror-based method was verified in a similar way. This time, the detector chip was installed on a 2-layer printed circuit board (PCB) made of 127-micrometer-thick low-loss laminate of dielectric constant \(\varepsilon_r = 2.2\), which is mechanically rigid but thin enough not to support substrate modes. There is no metallization in the central part of the PCB where the chip is located, so that the sub-THz radiation can propagate through the substrate and into the mirror with minimal loss.

First, the PCB was placed on a non-reflective support and its responsivity was measured. Then, the PCB was flipped over and fixed on the top surface of the brass block where the mirror was milled. The responsivity measurements of the mirror-based detecting system was repeated for mirrors of diameters of approx. 5.5, 9, 16 and 25 mm. Each time the same PCB-installed detector chip was used. No additional tuning of the system was done, yet. However, this is possible by using several versions of a given mirror that slightly differ with the machining depth so that accounting for inaccuracies in chip installation on the PCB is possible.

IV. RESULTS

The results obtained from measurements of the lens-based system are shown in Figure 1a. As a way to check if multiple reflections do not obscure the results, the measurements were done at two slightly different frequencies. The data show that by using the 9 mm plastic lens, the responsivity of the detector can be increased 13 times. As a comparison, the same scenario was modeled numerically using 3D electromagnetic (EM) solver QuickWave3D. The responsivity improvement was calculated by comparing the power gain of the plain detector which is cir. 7.94 dBi and the power gain of the same detector with the lens added which resulted in the estimated peak improvement factor of 16 occurring slightly closer to the lens. However, the calculations were done with the plane-wave assumption, while in reality the wave that illuminated the system was a Gaussian beam with divergence of 12°. Accounting for this fact with the well-known thin lens equation allows introducing corrections to the FDTD model.

The measurement data obtained for the mirror-based system suggest that the improvement factor is linearly dependent on the area of the mirror aperture, which is illustrated in Figure 1b. The mirror of diameter 9 mm improved the responsivity by 18 times, which could be attributed to lower losses than in case of the lens. With increasing the mirror size one can relatively easy achieve bigger increase in the responsivity of the MOSFET detector.

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V. REFERENCES