A Broadband 0.6 to 1 THz CMOS Imaging Detector with an Integrated Lens

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***Abstract*— This paper presents a lens-integrated terahertz imaging detector implemented in a 65 nm bulk CMOS process technology. The back-side illumination through a silicon lens increases the imaging SNR by 7-15 dB. The broadband detector design has been verified from 0.6 to 1 THz. At 1 THz the circuit achieves a noise equivalent power (NEP) of 66 pW/$\sqrt{Hz}$ and a responsivity (R_v) of 800 V/W for back-side illumination. The first 1 THz CMOS active imaging results with a lens are presented.**

***Index Terms*— Submillimeter wave detectors, submillimeter wave imaging, CMOS, terahertz direct detection, silicon lens, resistive mixer.**

I. Introduction

Sub-millimeter-wave integrated circuits based on CMOS and SiGe BiCMOS process technologies are becoming increasingly more interesting due to their high integration capabilities. In particular, large-scale multi-element phased arrays or focal-plane imaging arrays are attractive because the entire imaging system, including on-chip antennas, enables system-on-chip solutions [1]. For instance, a multi-element 820 GHz SiGe transmit/receive chipset for active terahertz imaging applications has been published in [2]. Direct square-law focal-plane arrays in CMOS were demonstrated at frequencies up to 650 GHz, with reported responsivities as high as 1.1 kV/W and NEP as low as 50 pW/$\sqrt{Hz}$ at 650 GHz in 65 nm SOI CMOS [3]. Other works include 650 GHz receiver in [4], above 1 THz power detection in [5], sources at 410 GHz in CMOS [6], and -8 dBm SiGe multiplier chains at 320 GHz in [7].

On-chip terahertz antennas are easy to implement in silicon process technologies, if a thick metal-stack (back-end of-the-line) is available. Most receiver systems at terahertz frequencies, however, work with optical systems with a large F/D number, and therefore, require antennas with directive patterns. In this paper, an extended hemispherical silicon lens was applied to solve this problem [8], [9], [10]. A broadband feed antenna and a new source-driven detector circuit were implemented in a 65 nm CMOS Bulk technology to achieve a broadband imaging detector with high SNR in active imaging applications. Compared to previously published gate-driven detector circuits in [2] (see Fig. 1 a), the circuit presented in this paper uses a source-driven approach which achieves broadband operation without additional tuning elements as shown in Fig. 1 b). In substitution of a capacitor, ac-grounds provide a more broadband connection of the drain to the gate. Details of the CMOS detector design and the implemented lens configuration are presented in Section II. Measured results are presented in Section III and Section IV presents active imaging results at 1 THz for the first time in CMOS technologies.

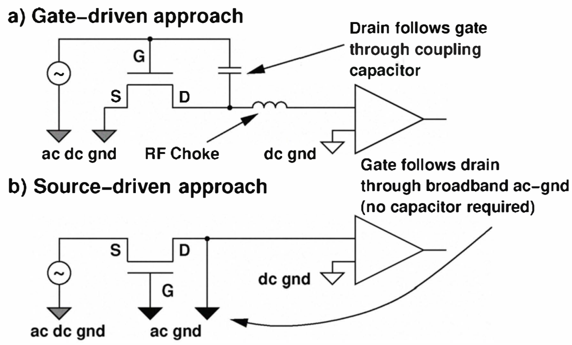

Fig. 1. a) A gate-driven self-mixing circuit topology requires a coupling capacitance and a narrow-band RF choke in order to drive the FET mixer and to isolate the low-frequency output from the RF signal. b) The source-driven topology, however, provides broadband operation without the need for additional tuning elements (ac-grounds).

II. Terahertz CMOS Detector Design

The terahertz square-law power detector is based on a differential pair of NMOS transistors provided with an on-chip folded dipole antenna. The RF power received by the antenna is converted into a dc current by distributed self-mixing [11] in the non-linear RC transmission line provided by the gate and channel of each transistor. Hence, the output voltage or current from the detector is proportional to the detected power.

A. Source-Driven Broad-Band Detector

Fig. 2 shows a circuit schematic of the implemented square-law terahertz detector. In contrast to the gate-drain coupling approach used in previous publications [11], the RF power from the antenna is provided to the source terminals of the two NMOS transistors T1 and T2 in the present design. The gate and drain terminals of the transistors are connected together, thus creating virtual grounds for the RF voltage. In

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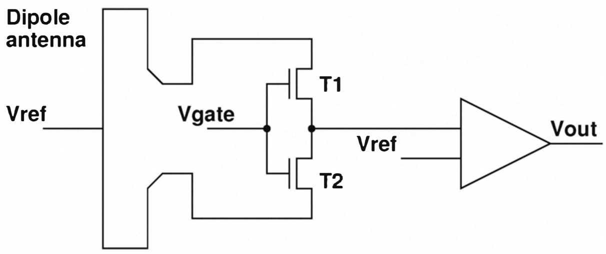

Fig. 2. Schematic diagram of the differentially configured source-driven distributed-mixing terahertz square-law power detector.

a balanced configuration, half of the RF signal generated by the antenna appears as a V_{gs} voltage across the gate-source junctions of each transistor and contributes to the distributed self-mixing process in the channel. The rectified output current or voltage is extracted from the shared drain node. This configuration eliminates the need for quarter-wave stubs and coupling capacitors, which are necessary in the gate-driven detector design [11] in order to tie the RF potential of the gate and drain together and to provide isolation of the output port from the antenna. Hence, a wider operating bandwidth can be obtained with the source-driven detector than with the gate-driven one.

Isolated-well transistors with gate dimensions of 1 μm width and 65 nm length were used in the detector design. The width of the devices was selected as a trade-off between high responsivity (small width) and low thermal noise voltage (large width) given the impedance-matching constraints of practical antenna implementations. A 36-dB gain voltage amplifier with a simulated 20 nV/$\sqrt{Hz}$ noise floor is integrated with the detector as an optional output buffer.

B. On-Chip Antenna Design and Packaging

The chip has been manufactured in a STMicroelectronics 65 nm bulk CMOS technology. The chip thickness is 235 μm and the bulk conductivity is 15 Ωcm. Multiple detector test sites have been arranged in a 3x5 array as shown in Fig. 3.

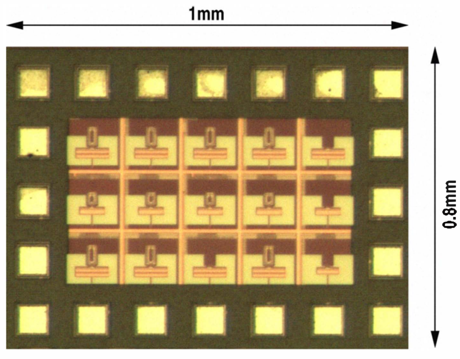

Fig. 3. Micrograph of the manufactured chip with multiple detector test sites.

An on-chip folded dipole antenna has been implemented using the top metal layer. The antenna provides a relatively large bandwidth and a balanced signaling. Another advantage of this antenna type is the high input impedance due to the asymmetric strip design [12]. The physical length of the dipole is 56 μm, which corresponds to a resonant frequency of 1 THz. The driven strip has a width of 2 μm, while the non-driven strip, is 10 μm wide.

The antenna supports different chip mounting and packaging configurations, which are illustrated in Fig. 4. Firstly, reflector-backed front-side illumination (Fig. 4 a) supports wire-bonding. Secondly, back-side illumination (Fig. 4 b) requires flip-chip mounting. Thirdly, a lens-integrated configuration (Fig. 4 c) is preferred, because the dipole acts as a feed for the lens, therefore increasing its overall gain and making it more suitable for coupling to a typical optical chain.

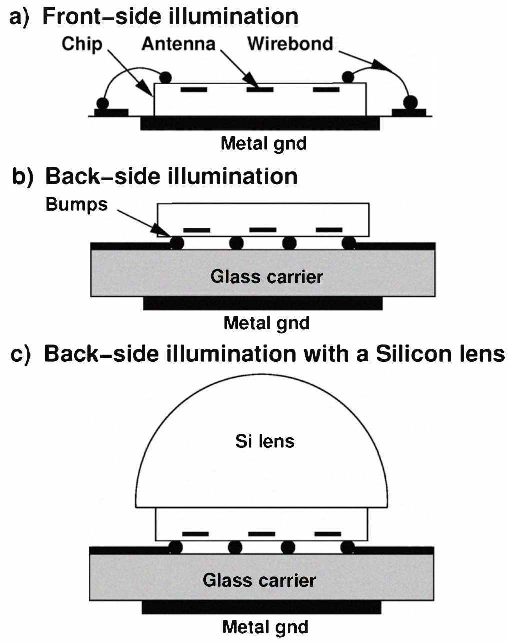

Fig. 4. The detector chip mounted for a) front-side radiation, b) back-side through-substrate radiation, and c) coupled to an integrated lens.

The three mounting configurations have been investigated by means of full-wave 3D EM simulations of the full array. Simulated results predict an antenna efficiency of 4-15% with a 8-10 dBi directivity across the 0.6 to 1.1 THz band for front-side illumination. The low efficiency is caused by strong excitation of substrate modes. It increases up to 30% for back-side illumination through a 235 μm thick silicon bulk material. With an infinite substrate thickness, the efficiency can be as high as 45-75%. The latter one corresponds to a thick anti-reflection coated silicon lens without multiple internal reflections. The simulation results are summarized in Fig. 5. The chip has been flip-chip mounted on borosilicate glass carrier for back-side illumination through a silicon hyper-hemispherical lens with a 3 mm diameter and a 1.8 mm thickness.

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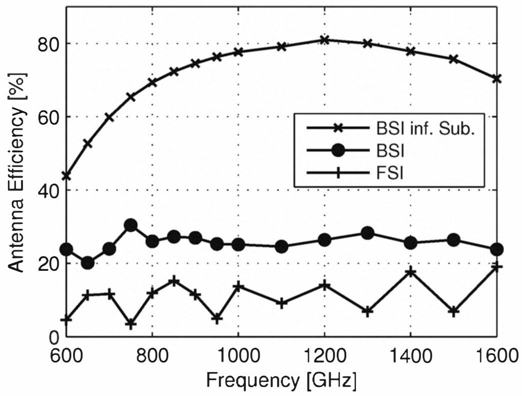

Fig. 5. EM simulation results of the on-chip dipole antenna efficiency in the front-side illumination (FSI) configuration, back-side illumination (BSI) with conductor backing, and with infinite substrate to emulate the conditions of an anti-reflective-coated lens (BSI inf. Sub.).

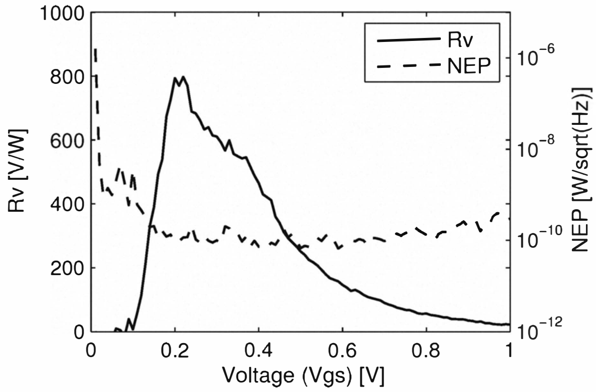

Fig. 6. Measured R_v and NEP in back-side configuration at 1027 GHz for a sweep of gate bias.

III. Measured Results

Free-space measurements of the implemented detector have been performed using an antenna-equipped terahertz 54× multiplier chain driven by a microwave synthesizer with a distance of 2 cm. The multiplier chain provides an output power of 1-10 μW with a 25-dBi diagonal horn and is tunable over the 0.6-1 THz frequency range. The output power is modulated (chopped) by a 1 kHz square wave to facilitate detection with a lock-in amplifier. A 60-dB external preamplifier is connected directly at the output of the THz detector, thus bypassing the integrated buffer amplifier. A lock-in amplifier is used to recover the detector output voltage at the modulation frequency.

The R_v of the detector was calculated from the detected output voltage divided by the available power to the pixel. For back-side illumination without an attached lens, the available pixel power was derived from the irradiance at the plane of the detectors multiplied by the 150×150 μm^2 large pixel area. The silicon lens will increase the effective antenna area and can be calculated from the simulated value of the the antenna directivity. The irradiance in both cases was calculated using the Friis transmission equation based on the measured output power of the source, the known horn antenna gain, and the known distance to the source including the reflection coefficient and the losses of the lens configuration. The NEP is derived from the measured detector noise voltage divided by the responsivity R_v. All results exclude the gain of additional measurement amplifiers. The measured R_v and NEP are shown in Fig. 6. At 1.027 THz the maximum non-amplified R_v is 800 V/W and a minimum NEP is 66 pW/$\sqrt{Hz}$ for a gate bias of 0.2 V and 0.4 V respectively.

From 660 GHz to 1027 GHz the measured R_v is between 200 V/W and 1.2 kV/W in the back-side illumination and between 480 V/W and 800 V/W with lens as shown in Fig. 7. The variation of the measured R_v of the detector with the lens is less than 3-dB within a frequency range of 600 GHz to 1 THz. This shows the broadband behavior of the detector with the lens in comparison to the back-side configuration, with a 3-dB bandwidth of at least 400 GHz. This measurement correlates well with the simulated antenna efficiency shown in Fig. 5, taking into account antenna coupling to multiple resonances and substrate modes present in the back-side illumination with and without lenses. Verifying the R_v beyond 1 THz is only limited by the available measurement equipment. This bandwidth is attained due to the enhancement of the directivity and the efficiency of the integrated antenna by using Silicon lenses, as well as the broadband behaviour of the detector circuit.

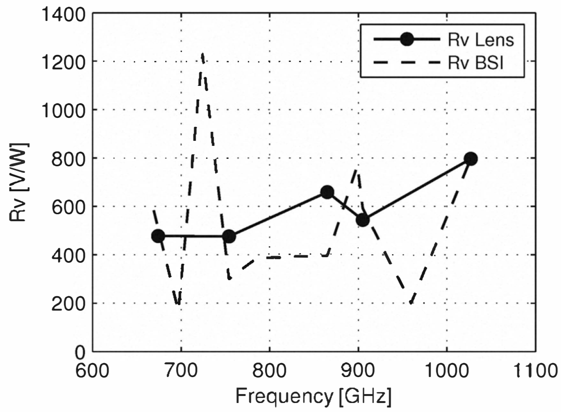

Fig. 7. Maximum R_v versus frequency in lens configuration in comparison to back-side illumination behavior.

The inclusion of the silicon lens improves the detector output signal and the bandwidth, it increases the antenna efficiency and also the antenna gain, which improves the coupling to an external THz imaging system. Fig. 8 shows the measured SNR improvement in an active THz imaging system. From 660 GHz to 1027 GHz the detector output, including a silicon integrated lens, increases by 7-15 dB versus back-side illumination without a lens.

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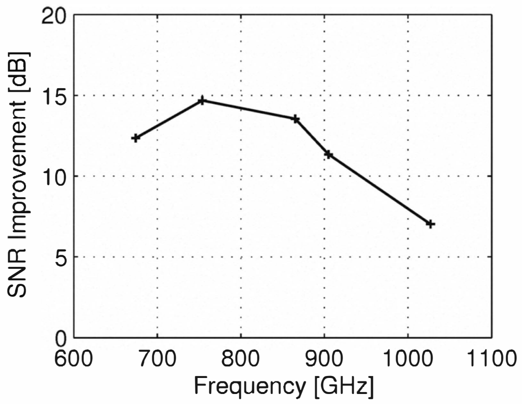

Fig. 8. Measured SNR improvement in an active THz imaging system for a 3-mm silicon hyper-hemispherical lens.

IV. Terahertz Imaging

The broadband THz detector circuit is used with a silicon lens glued at the back-side of the die. A 600 GHz to 1.1 THz multiplied source is used to illuminate the object to be scanned. Fig. 9 shows two different objects imaged at 1.027 THz. The objects are mechanically scanned in transmission mode over the vertical plane at the focal point of the optical setup. Fig. 9 shows the optical and 1 THz images of a plastic badge with a hidden knife, and a paper envelope containing different objects. The 1 THz images clearly reveal the metallic objects hidden within plastic or paper packages with considerably fine resolution.

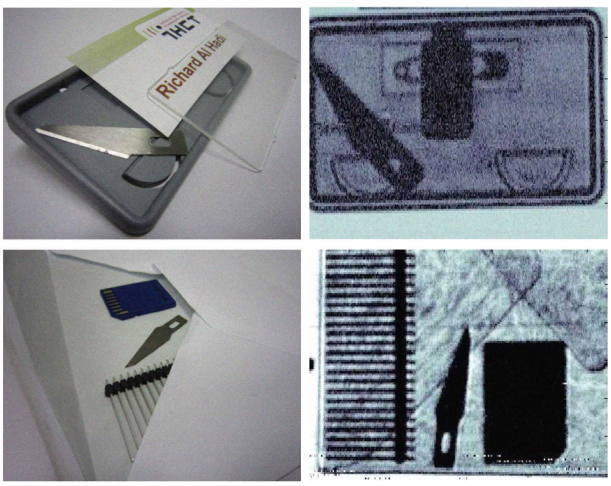

Fig. 9. Transmission-mode images at 1 THz of a badge and an envelope.

This novel CMOS imaging detector provides the felxibility of object-scanning at a broad range of spatial resolutions, with the resolution increasing with the transmission frequency. The image sharpness and depth are significantly enhanced as the SNR of the system is increased. This enhancement is mainly due to the increase of the detector responsivity as well as the use of the silicon lens, which widens the dynamic range of the detector and increases the antenna directivity.

V. Conclusion

This paper presents a lens-integrated terahertz imaging detector fully implemented in an industrially available 65 nm CMOS process technology. A novel source-driven approach, achieves broadband operation without additional tuning elements and a hemispherical silicon lens was applied to provide directive patterns for terahertz imaging with a 7-15 dB improved SNR. At 1 THz the circuit (without lens) achieves an NEP of 66 pW/$\sqrt{Hz}$ and a R_v of 800 V/W. The implemented pixel test-site includes low noise operational amplifier and demonstrates the capability of fully integrated CMOS THz camera chips.

Acknowledgments

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