A Terahertz Imaging Receiver in 0.13µm SiGe BiCMOS Technology

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***Abstract* — This paper presents an integrated THz imaging receiver in bulk 0.13µm SiGe technology. The receiver, based on direct power detection, achieves a peak responsivity of 2.6MV/W and 700kV/W and a NEP of 8.7pW/√Hz and 32.4 pW/√Hz at 0.25 THz and 0.3 THz, respectively. No external silicon lens or post-processing, such as substrate thinning, was employed for improving antenna gain, efficiency and reducing power loss in substrate modes. To the best of the authors' knowledge, this is the lowest reported NEP in silicon at THz frequencies, without the use of expensive post-processing or external silicon lens.**

I. Introduction and Background

Silicon technologies, with rising f_t and f_{max} in progressively scaled nodes, present promising low-cost alternatives to III-V semiconductor technology. However, ohmic losses in doped bulk silicon substrate and substrate-wave excitation severely limit integrated antenna efficiency, leading to lower responsivity and higher NEP at THz frequencies. Expensive corrective measures such as custom high-resistivity silicon substrates, silicon lens, and substrate thinning can increase performance, but it comes with high post-processing cost and in a certain way, self-defeats the philosophy of low-cost, fully integrated THz imagers [1]-[3].

In this paper, we demonstrate how a co-design of electromagnetics and circuit can mitigate many of these issues and pave the way for a truly fully-integrated THz imager. The THz imaging receiver, presented in this paper, achieves a peak responsivity of 2.6MV/W and a NEP of 8.7pW/√Hz at 0.25THz in 250 µm bulk silicon with 10 Ω-cm resistivity. The receiver is particularly suitable for integration into a multi-pixel 2D THz imager. The performance compares well with commercially available Golay cells (NEP of 100-400 pW/√Hz), Schottky Barrier Diodes, and Micro-bolometers (~20 pW/√Hz) [1].

II. Technology and Design

The THz receiver is based on direct power detection and implemented in a 0.13µm SiGe BiCMOS process (f_t, f_{max}~200/265 GHz) on bulk silicon substrate. The receiver in silicon, along with circuit schematic, baseband amplification, and the integrated antenna is shown in Fig. 1. Since the frequency of operation of the receiver is near and above the f_{max} of the technology, a LNA with power gain cannot be realized and therefore the antenna is immediately succeeded by a detector. The antenna is a loop antenna with a modified ground plane, realized on 4µm thick top Al layer. The loop antenna excites the ground plane aperture, which exploits the high permittivity of silicon to radiate though the substrate from the backside of the chip as shown in Fig. 2. The aperture and the detector are co-designed for conjugate matching, maximum power transfer and minimizing power loss in substrate modes. [4]-[6]. The ground plane maximizes radiation from the back of the chip by preventing waves reflected from the substrate-air interface to leak out from the top of the chip. The detector is optimized for lowest NEP. The simulated responsivity and NEP of the antenna-coupled detector are 6.5KV/W at 5.2pW/√Hz respectively at 0.25 THz with a chopping frequency of 5 KHz.

To increase the responsivity of the receiver, the detector is succeeded by a chain of baseband amplifiers with controllable gain. In order that the response of an incoming radiation is not swept by the 1/f noise or the offsets in the circuit, the incoming radiation is to be chopped at a frequency lying beyond the 1/f corner. The baseband amplification chain is designed to have a bandpass response where the lower frequency corner can be varied on-chip from 100Hz-1KHz and the upper frequency corner is around 1MHz. The baseband amplification has a tunable gain from 33.0-57.7 dB for a high dynamic range.

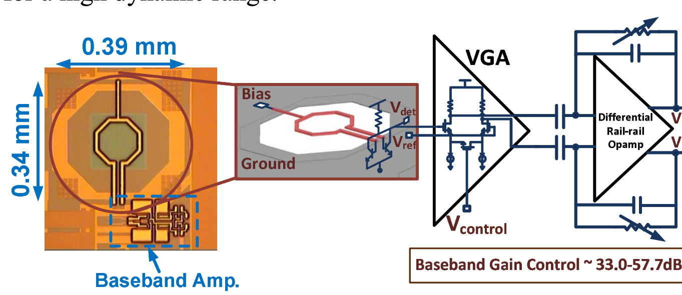

Fig 1. THz imaging receiver in silicon with schematic, integrated antenna, and baseband amplification with 24.7dB tuning range

III. Measurement Results

The experimental set up for responsivity and NEP measurements is shown in Fig. 2. The radiation is captured by the chip form the backside of the substrate where it has the highest directivity.

Responsivity is characterized in the far-field of a WR-3 source and the noise profile is measured using a spectrum analyzer, buffered by an external LNA. The THz radiation was chopped at a frequency of 5 KHz and the baseband output was observed in an oscilloscope. The whole setup was calibrated with an Erickson power meter. The receiver was irradiated with measured 390nW and 160nW of power at 0.25THz and 0.30 THz, respectively, at a far-field distance of 50 mm. The measured responsivity and NEP of the receiver in the WR-3 band is shown in Fig. 3. The receiver achieves a peak responsivity of 2.6MV/W and 700kV/W, and a NEP of 8.7pW/√Hz and 32.4 pW/√Hz at 0.25 THz and 0.3 THz respectively. To the best of the authors' knowledge, this is the lowest reported NEP in silicon at THz frequencies, without using expensive post-processing or external silicon lens. Simulations predict that substrate thickness optimization through back-lapping can achieve a NEP of near 4 pW/√Hz, comparable to typical noise performance achieved in cooled micro-bolometers [1].

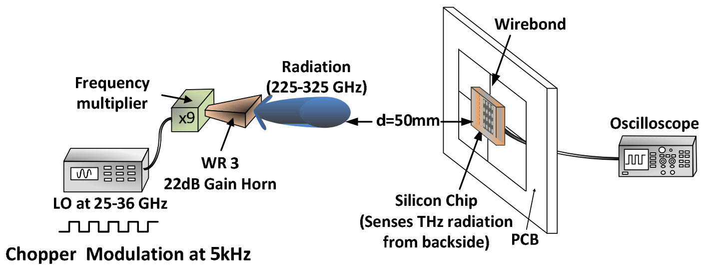

Fig 2. Measurement set-up showing chopped THz radiation captured from the backside of the silicon die

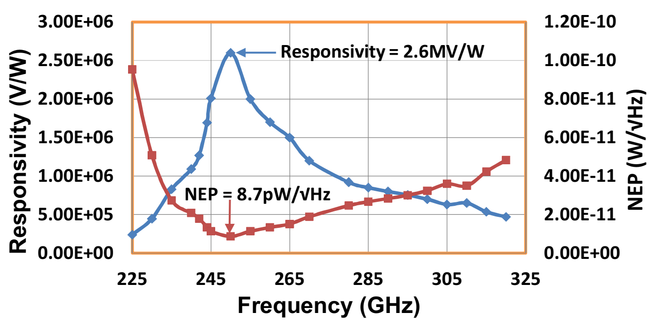

Fig 3. Measured peak responsivity and NEP of the receiver

Fig. 4 shows a measurement set-up for imaging the focused THz beam to a diffraction limited spot. The radiation is again captured from the backside of the silicon die and the output is measured by a locking amplifier synchronized with the chopping signal. The PCB is connected to a motorized translational stage. The chip is raster scanned over the focal plane of 5mm x 5mm, and the output voltage is plotted in a 2D plane. Thereby, the constructed image of the beam over the focal plane is shown in Fig. 5. The full-width at half-maximum of the Gaussian beam is shown to be approximately 1mm at 0.26 THz.

The results indicate that high-performance imagers can be built in silicon without the need of substrate thinning and silicon lens. Careful electromagnetic design can reduce substrate mode coupling of integrated antenna to a large extent, negating the need for external post-processing. The paper illustrate that codesign of circuits and antennas together can overcome many challenges of building sensitive THz imagers in low-resistivity, low f_{max} bulk silicon processes, that can compete with customized commercially available Golay cells, Schottky Barrier Diodes, and Micro-bolometers.

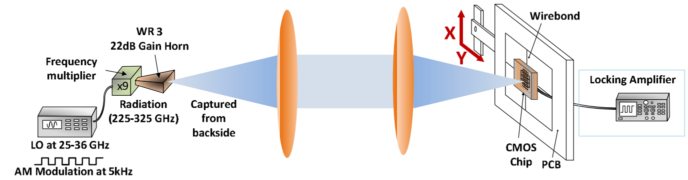

Fig 4. Measurement set-up for focusing emitted THz beam to a diffraction limited spot size on the focal plane which is imaged by the THz receiver by raster-scanning.

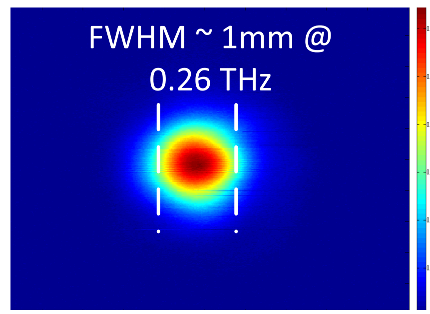

Fig 5. Measured spot size of the focused beam at 0.26 THz on the focal plane.

IV. Conclusion

This paper presents an integrated THz imaging receiver in bulk 0.13μm SiGe technology. The receiver, based on direct power detection, achieves a peak responsivity of 2.6MV/W and 700kV/W and a NEP of 8.7pW/√Hz and 32.4 pW/√Hz at 0.25 THz and 0.3 THz, respectively. A careful design of electromagnetics, circuits and radiating structure eliminates the need for any external silicon lens or post-processing, such as substrate thinning, for improving antenna gain, efficiency and reducing power loss in substrate modes. To the best of the authors' knowledge, this is the lowest reported NEP in silicon at THz frequencies, without the use of expensive post-processing or external silicon lens.

References

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