On-Wafer Metrology for a Transmission Line Integrated Terahertz Source

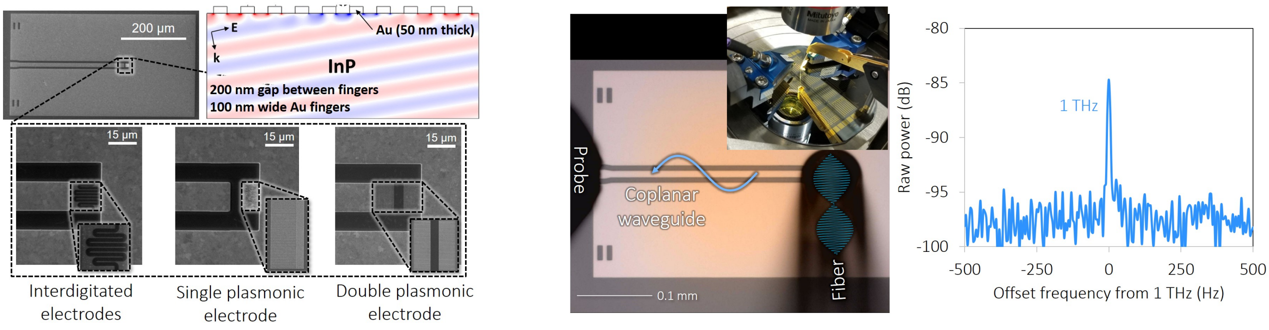
Kassiopeia Smith*, Bryan Bosworth, Nicholas Jungwirth, Jerome Cheron, Nathan Orloff, Christian Long, Dylan Williams, Richard Chamberlin, Franklyn Quinlan, Tara Fortier, and Ari Feldman
National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305 USA
**send correspondence to: kassiopeia.smith@nist.gov*

Abstract

We developed a measurement system that combines on-wafer metrology and high-frequency network analysis to characterize the response of transmission-line integrated Er-GaAs and InGaAs photomixers up to 1 THz to support the telecommunication and electronics industry. © 2020 The Author(s)

Radio frequency (RF) test equipment is used in the electronics and telecommunications industry to characterize electronic devices from DC to above 1 THz. Commercial semiconductor foundries need proper high-frequency diagnostic signals to reduce the time-intensive and costly trial-and-error process during development of next-generation wireless communication, computer processing, and other high-speed electronics [1–3]. Complex modulated-signal tests use arbitrary waveforms that are generated by discrete digital steps to construct analog signals, but are fundamentally limited in frequency based on the operating frequency of the digital circuit. Drawbacks to the current RF approach include frequency-banded rectangular waveguides, amplification of phase noise, and poor stability caused by multiplying the RF source to the desired frequency. While interleaving multiple digital sources is one way to overcome the issue, amplitude fluctuation, timing jitter, and noisy signals above 40 GHz remain an issue [4].

Here, we present a broadband optoelectronic source for linear and non-linear network analysis of wafer-based devices and the first steps toward a terahertz synthesizer. We first separate individual frequencies of an optical comb and pass them through a phase-and-amplitude control array that steers the optical frequencies to a fiber. The modulated signals in the fiber are converted into an electrical signal by dividing the frequency down with a photomixers that operate to a terahertz. As a part of this new signal generation paradigm we grew erbium doped GaAs and InGaAs photomixers via molecular beam epitaxy on semi-insulating InP substrates and defined electrodes and co-planar waveguide structures using traditional and electron-beam lithography techniques. We leveraged recent advances in the photomixer field to simulate and incorporate plasmonic electrode structures to enhance terahertz conversion efficiency. Figure 1a shows SEM images of the fabricated devices as well as a multiphysics simulation of the plasmonic enhancement of the optical absorption. Two teeth of an optical frequency comb source excited the photomixers, and a WR1 wafer probe and extender head connected to a vector network analyzer measured the output signal up to 1 THz. Fig. 1b shows the measurement setup and initial data.



(a) (b)

Fig. 1: a) Optical and SEM micrographs of a transmission line integrated photomixer device and example plasmonic electrode simulation. b) On wafer measurement of devices using frequency comb optical beat

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There are a large number of industries that rely on electronic devices that operate over a terahertz and currently no way to measure or calibrate devices that operate within that frequency regime. Continuous-wave (CW) terahertz photomixing devices have emerged along side a number of advances to photoconductive materials, electrode design, operating frequency, and conversion efficiency [5]. $In_{0.53}Ga_{0.47}As$ grown on semi-insulating InP substrates allow utilization of low-cost and readily available Er-doped fiber lasers that operate at 1550 nm. While InGaAs is a promising material, there is room to reduce dark current and increase optoelectronic conversion efficiency [6]. InGaAs offers much higher mobilities than the more commonly utilized LT-GaAs, but suffers from lower conversion efficiency at typical bias voltages [7–9]. Implementing advanced growth techniques such as incorporated nanostructures and Bragg reflectors are ways to improve bandwidth, increase signal output, improve resistivity, and add the ability to tune photocarrier lifetimes.

Historically, high-frequency photomixer devices have been intended for terahertz radiation. They are operated by pumping an ultra-fast mode-locked laser onto the electrode contact and measuring the radiated power as a function of bias voltage and optical pump power. Alternatively, fabrication of co-planar transmission-line integrated photomixers with terahertz output represents an innovative advancement for on-wafer metrology. When the photomixer is excited by the heterodyned beat of two tones from an optical frequency comb a high fidelity terahertz signal is generated and can be used as a convenient on-wafer source. Dividing down from the optical regime reduces phase noise at these frequencies, as opposed to traditional multiplication which increases phase noise. Through on-wafer metrology techniques, the propagation constant and dispersion effects of the transmission line can be solved for, which allows the reference plane to be rolled to a plane of interest. For example, when using a photomixer as a source, it will need to be coupled to or embedded within a device or material of interest and the reference plane can be rolled to that interface [10]. Furthermore, when a device is fabricated on an electro-optic substrate, optical network analysis techniques can be used to examine the outgoing and reflected waves of devices under test [11]. The ability to generate pure sine waves up to 1 THz and optically measure outgoing waves and their reflection off a device or material-under-test is a useful measurement tool that will enable development of next-generation technologies with first-pass design success [12].

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