Probing Live PN Junctions with Terahertz Waves

Bryce Chung[1], Harrison Lees[1], Chitchanok Chuengsatiansup[2], Withawat Withayachumnakul[1]
[1]Terahertz Engineering Laboratory, The University of Adelaide, Australia
[2]School of Computing and Information Systems, The University of Melbourne, Australia

***Abstract*—It is known that the reflectivity of semiconductor materials at terahertz frequencies is sensitive to changes in free carriers. This phenomenon has been rigorously studied with semiconductor wafers and offline semiconductor devices. Despite this capability for sensing free carriers, terahertz probing of semiconductor devices in operation is nearly non-existent. Here we observe a PN-junction diode in operation, using terahertz waves in reflection. The Shockley diode equation and Drude model are leveraged to explain the observation. We anticipate that this work will be fundamental in establishing the capability to monitor semiconductor devices in operation, potentially unlocking a new wave of terahertz applications in the semiconductor industry and beyond.**

I. INTRODUCTION

An important research area since the inception of modern terahertz science is non-contact spectroscopy of semiconductor materials. A key finding from earlier studies is that moderately doped semiconductors have their plasma frequencies and damping rates lying in the terahertz range [1], [2]. An implication is that terahertz waves are highly sensitive to free carriers and their dynamics [3]. Interestingly, while a vast number of terahertz spectroscopy experiments have been conducted on semiconductor wafers subject to different stimuli, the idea of non-contact terahertz probing of semiconductor devices during operation remains vastly unexplored. As a preliminary study, we report a relationship between changing carrier concentrations and terahertz characteristics in a biased PN-junction diode. From experiments conducted with a vector network analyser system, changes in reflectivity are observed to correspond to the live adjustment of bias current.

II. EXPERIMENT

In the experiment, a 1N4148 silicon epitaxial planar diode is subject to terahertz probing. The diode is placed in a focused terahertz beam according to Fig 1(a,b). As illustrated in Fig 1(a), two 3D printed cyclic olefin copolymer lenses collimate and focus the terahertz beam from the horn antenna, forming a spot on the diode with a $1/e^2$ width of 3.5 mm. The sourcemeter sweeps the diode bias voltage from -1 to $+1$ $\mathrm{V_{DC}}$ over 1000 steps, measuring voltage and current at each step. Simultaneously, the Precision Network Analyser (PNA) records complex S_{11}, i.e. reflection, measurements at each bias voltage over 220–330 GHz. This measurement is coordinated via a Python script.

III. RESULTS AND DISCUSSION

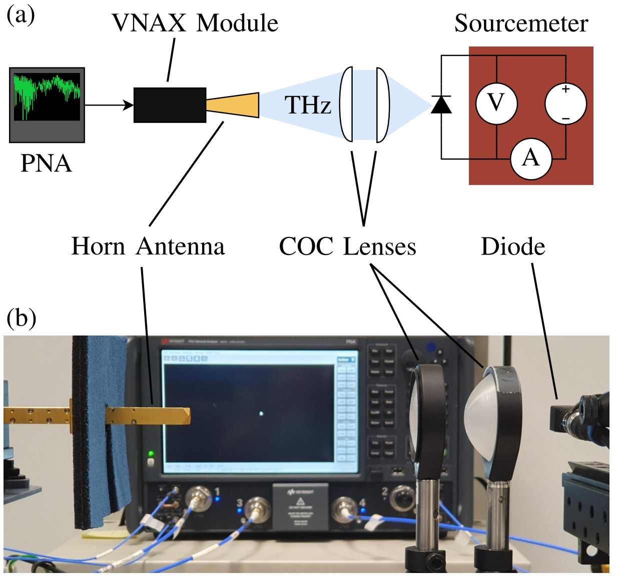

Fig. 1 Diagram and photo of the experimental setup used to measure complex S_{11}. (a) The Precision Network Analyser (PNA) is configured in series with a Vector Network Analyzer Extension Module (VNAX) to measure S_{11} over 220–330 GHz. Custom 3D printed cyclic olefin copolymer lenses collimate and focus the beam from the horn antenna to a 3.5-mm spot on the diode. (b) The diode is retained in a screw terminal block and held 35 mm away from the focusing optic.

The first step is to estimate the change in carrier concentration within the PN junction by fitting the Shockley diode model [4] to the measured IV curve of the diode. Fig. 2(a) shows reasonable fit, with some discrepancy in the ideality factor attributed to low diffusion current in the widened depletion region at low bias voltage. The carrier density is estimated from the parameters fitted to the Shockley model [4], and then substituted into the Drude model [5] to estimate the change in permittivity over the swept bias voltage. An assumption made is that the space charge region in the diode is homogeneous. It is expected that as carrier concentration increases due to an increase in bias voltage, the junction essentially acts like a metal. This effect is manifested by the Drude model as the real component of permittivity drops below zero as shown in Fig. 2(b).

To further emphasise this point, an inverse Fourier transform is performed on every S_{11} measurement collected, providing time domain data at each bias voltage. Peaks in the time domain correspond to strong reflections off of the internal structure of the diode. The two peaks illustrated in Fig. 2(c) represent the front and back surfaces of the semiconductor. Tracing the amplitude of the two prominent peaks labelled in Fig. 2(c) across bias voltage, a change is visible in Fig. 2(d) at a bias voltage of around 0.7 $\mathrm{V_{DC}}$. This voltage is close to the junction voltage of $V_J = 0.869\ \mathrm{V_{DC}}$ obtained from a SPICE model. The reflection coefficient modelled from the change in complex permittivity is presented alongside the time domain peak traces, showing similar inverted trends at the same bias point. This phenomenon is attributed to the semiconductor becoming more conductive and metallic, leading to higher reflectivity in the diode. As more power is reflected by the front surface, less power is available to be reflected off back, leading to a decrease in time domain amplitude and the inverse relationship between both peaks.

IV. CONCLUSION

This work shows that terahertz waves are able to detect the change of free carriers in a diode in response to the adjustment of bias voltage. A preliminary analysis leverages the Shockley diode equation and Drude model to explain the carrier dynamics and effects on reflectivity of the diode's internal structure. Examination of the diode structure in the time domain yields trends that support the proposed model. This collection of results and analysis serve as an indication that much more research is possible in this area, potentially unlocking new applications for terahertz waves in the live monitoring of integrated circuits and high-power semiconductor electronics.

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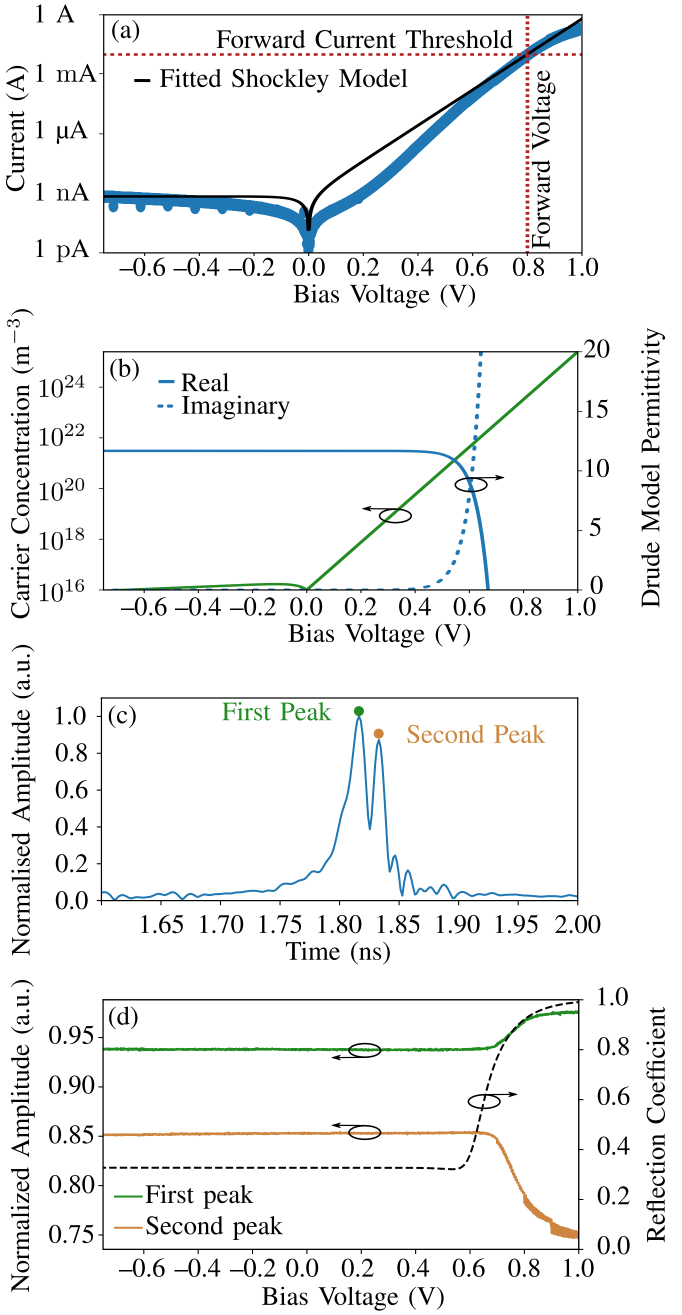

Fig. 2 IV and S_{11} measurements. (a) Diode IV curve and fitted Shockley model. The red dotted line indicates the forward voltage at which the IV curve becomes linear and deviates from the Shockley diode equation. (b) Carrier concentration extracted from Shockley model and estimated permittivity from Drude model. (c) Time domain from S_{11} measurement averaged over -1 to $+1\mathrm{V_{DC}}$. (d) Time domain peak values over bias voltage, plotted against modelled reflection coefficient.