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Data Article

Semi insulating N-gallium nitride (GaN) on sapphire surface reflection dataset obtained at millimeter wave frequencies 107.35–165 GHz

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ABSTRACT

A systematic collection of voltage reflection data for semi-insulating N-GaN wafer surface along with the reference reflection voltages are accomplished using a very stable continuous wave (CW) frequency stable probe source. The 2″ diameter direct-bandgap 5 µm silicon doped 10^5 Ω-cm GaN on 434 µm sapphire is a commercial sample and was mounted in the path of collimated BWO generated millimeter wave beam with spot size ~3 mm and rotated 64.5° to millimeter wave reflected energy into an antenna fed zero-bias Schottky barrier diode (ZBD), a negative polarity detector with responsivity 3.6 V/mW. Data obtained pertain to photon energies between 400 and 700 µeV (107.35–165 GHz). Data contains the 30-sample average and respective standard deviations for reference (mirror) and N-GaN reflected voltages. Anomalies in d.c. reflection coefficients (based on the raw data) are identified for users.

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Specifications Table

Subject	Physics
Specific subject area	Millimeter wave dielectric property of commercial grade direct-bandgap semi-insulating Gallium Nitride (GaN) on sapphire wafer
Type of data	Floating-point (E-notation) raw tabular data pertaining to reflection of probe beam at each frequency; ASCII delimited CSV file (time and voltage); Figure showing spectrum of D.C. voltages captured after reflection from wafer surface by zero-bias Schottky detector diode (ZBD)
How data were acquired	Commercially acquired 10^5 Ω-cm N-GaN wafer and a highly polished gold mirror surfaces were used to reflect continuous ∼0.3 mW millimeter-wave probe beam at an angle of 64.5° and acquire detected voltage signal of the reflected probe beam using the ZBD and Time-Resolved Millimeter Wave (TR-mmWC) apparatus. Apparatus consists of Elva-1 SGMW-PLL series D-band backward wave oscillator (BWO) sweeper generator operated with frequency accuracy $\sim \pm 0.1\%$ and single lens horn antenna and controllable using LabVIEW 2017, a ZBD with noise equiv. power $\sim 2\text{pW}/\sqrt{\text{Hz}}$) with antenna, a set of 3 collimators and one focus poly-4 methyl pentene-1 (TPX) lenses, and a Keithley 2782 digital multimeter (DMM). The sample was rotated with respect to the millimeter wave beam path (64.5°) and direct current (d.c.) output of reflected frequency swept RF power (voltage signal acquired through detector) using antenna fed Schottky barrier diode with a bias-tee, averaged using DMM, and stored in files using LabVIEW
Data format	Raw Floating-point, ASCII delimited .CSV (comma separated variable)
Parameters for data collection	BWO probe beam reflected power was maximized by adjusting optical elements and fine orientation of wafer surface; The BWO frequency was swept using LabVIEW virtual instrument software architecture (VISA) with standard I/O resource and same for the Keithley model 2782 digital multi-meter (DMM) data acquisition and averaging; BWO start and end frequencies were 107.35 GHz and 165 GHz and was swept with delay 500 ms every increment of 0.1 GHz; DMM acquired 30 samples for each frequency hold and provided standard deviation and mean of the acquired voltages at each frequency point
Description of data collection	The sweeper generator was warmed up for 30 min, millimeter-wave (mmW) reflected beam power was maximized using highly polished mirror and by adjusting the lenses and orientation, ensure polarizer passing only vertically aligned electric field, mmW probe beam was turned on at 107.35 GHz and probe beam power was maximized by adjusting the optical elements in the system; The gold mirror was used first for collecting the reference voltages while the frequency is swept using LabVIEW virtual instruments code. A constant visual quality control procedure was maintained using LabVIEW graphical outputs to assure the data does not show spurious signals such as standing waves, etc. LabVIEW then holds the data acquisition until step 2. In step 2, the mirror is removed and the SI N-GaN wafer is mounted at the same inclination as the mirror, and LabVIEW VI code is one again initiated to acquire the sample surface reflection voltages at each of the probe frequency. The files with ASCII data are then stored in .CSV format and archived.
Data source location	North Carolina Central University Durham/North Carolina/Piedmont U.S.A. Lat./Lon. 35.97° N/ 78.89° W
Data accessibility	Repository name: Mendeley, https://data.mendeley.com/datasets/892sn9w7g4/3 DOI: 10.17632/892sn9w7g4.3#file-aa6a2796-5dd9-4944-8ac7-e1bd2660b920 filename: “D.C.-N-GaN-On-Sapphire-110-160GHz-reflection”
Related research article	Authors’ name: Biswadev Roy, Charles R. Jones, B. Vlahovic, Harald Ade, and Marvin H. Wu Title: A time-resolved millimeter wave conductivity (TR-mmWC) apparatus for charge dynamical properties of semiconductors Journal: Review of Scientific Instruments DOI: https://doi.org/10.1063/1.5026848

Value of the Data

- Silicon-doped [1] N-GaN on sapphire with C-plane (0001) is an important electronic material used for sensors, amplifiers, power and control devices, and photoluminescence. 2-photon absorption (TPA) process is an important property of GaN wafers [2]. TPA uses frequency dependent refractive indices. Reflectance used for evaluating dielectric and optical metrics. This data will enable users directly compute coefficient spectrum in the unique probe range 107.35–165 GHz.
- N-GaN reflection coefficients have been earlier published by Akinlami and Olateju (2012) [3] in the photon energy range 2 to 10 eV. These data pertain to much lower photon energies in regime 444 µeV to 682 µeV and with energy resolution 413 neV (0.1 GHz interval). They can be used to infer accurate dielectric properties such as relative permittivity. Interference patterns can be used to infer the refractive index, especially for circuit elements made for the fifth generation wireless (5 G) and internet of things (IoT) applications.
- This data corresponds to radiating far-field distances (space where radiation pattern does not change with distance) [4] between 83.14 mm to 129.6 mm respectively and is unique set of data obtained in free space configuration.
- Industry standard millimeter wave test methods involve microstrip differential phase length and ring-resonator methods mostly in the transmission through material under test (MUT) [5]. This data is reflection coefficient measured in free space method and may be very useful to supplement industry methods to ascertain the dielectric constant.

1. Data Description

Comma Separated Variable (.csv) file is shared in Mendeley.com. Column 1 is frequency in GHz, columns 2 is reflected voltage captured by the ZBD and averaged by the DMM when polished mirror is used, column 3 is standard deviation of the mirror reflected voltage. Columns 4 and 5 are the same as columns 2 and 3 except when Si GaN on sapphire is used as the mmW reflector. In entire experiment there is no light excitement of the sample. The RF voltage magnitudes are obtained under dark conditions only. Fig. 1 shows the reflected voltage spectra for

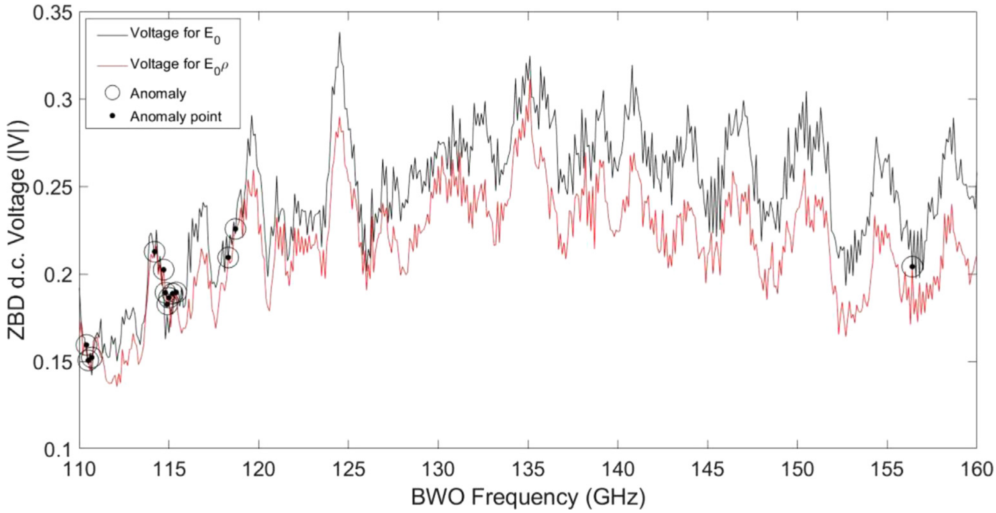

Fig. 1. Shows the reflected voltage |V| spectra of the reference gold mirror (in black) and the N-GaN wafer surface (in red). Anomalous data in reflection possibly due to standing wave or multiple reflections. N-GaN data are flagged for 110.4, 110.5 110.7 114.2 114.7 114.8 114.9 115.0 115.2 115.4 118.3 118.7 156.4 GHz.

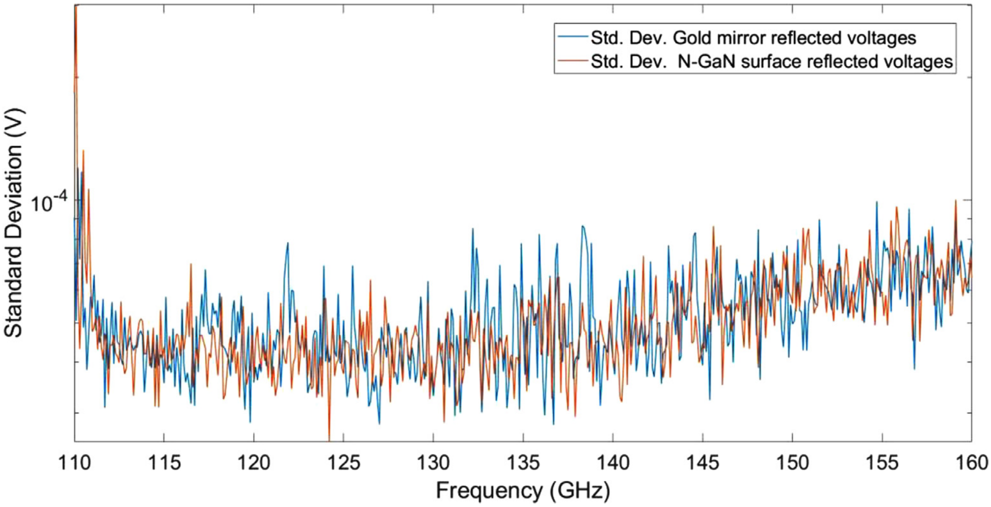

Fig. 2. Shows the 30-sample standard deviations spectra of voltage data acquired after reflection from the reference gold polished mirror (blue) and from N-GaN surface (orange) from the Keithley 2782 digital multimeter for each of the swept frequency point.

reference gold mirror reflector and N-GaN sample. An averaging of 10–30 samples is performed at each frequency point, and the data are stored in columnar fashion. Some of the sample reflection data show anomaly (points identified with a circle in Fig. 1) where sample reflected voltages are found to exceed gold mirror reflected voltages for the same frequency and power level. Those points must be excluded from use for data applications. Exact frequencies of these anomalous reflection data are also mentioned in the Fig. 1 caption below. With reference to the DC voltage spectrum given in Fig. 1 it needs to be pointed out that the N-GaN wafer (5 µm thick) is epitaxially grown over a 434 µm thick sapphire substrate resulting in multiple surfaces from where the electromagnetic energy get reflected, hence, for an incident millimeter wave beam on the GaN surface the detector responds to multiple reflected components of the return signal due to those surface discontinuity. The noise in DC signals can only be minimized by use of a thick wafer of the material under testing, instead of growing film on a substrate. Corresponding spectra of standard deviations for the gold mirror reflected reference voltages, and the N-GaN surface reflections are plotted in Fig. 2.

2. Experimental Design, Materials and Methods

We have used a newly developed quasi-optical, free-space, time-resolved millimeter wave conductivity (TR-mmWC) system [6] operated in the D waveguide-band (107.35 GHz to 165 GHz) with 0.1 GHz resolution to acquire surface reflected probe beam voltages from high resistivity (10^5 Ω-cm) 5 µm silicon doped N-GaN on sapphire substrate. The source for millimeter waves is the backward wave oscillator (BWO) with a spot diameter ~3 mm, and GaN sample is of commercial grade, and is rotated at an angle of 65.4° from the probe beam direction. Probe beam photon energies are in the range 0.4 to 0.7 meV. GaN refractive index for 532 nm laser pulse is 2.33 with large penetration depth compared to its thickness. BWOs are highly coherent sources and this system has extremely good frequency stability [7,8]. It is a phased locked BWO source capable of providing extraordinary frequency accuracy $\sim \pm 0.01\%$ in CW mode with full one band sweep period less than 200 µs. The frequency stability for 15 min is 2×10^{-4} with outputs voltage standing wave ratio 1.5. It has an impressive output power regulation range ~ 0–10 dB (controlled situation).

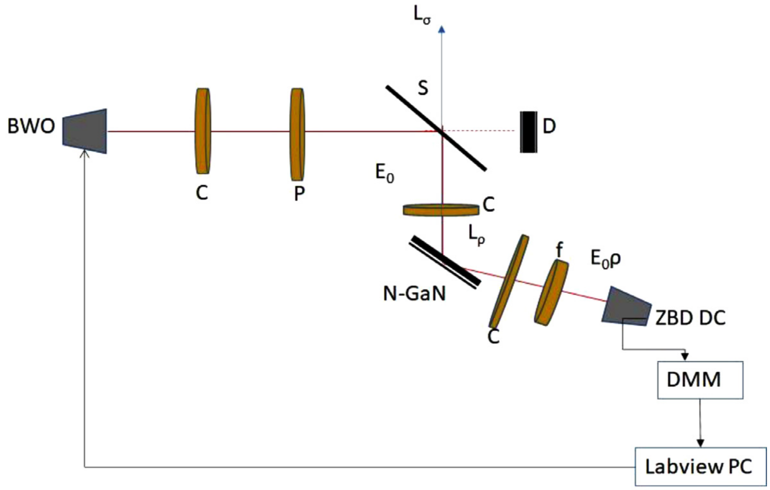

Fig. 3. Shows the schematic for the TR-mmWC data acquisition system using TPX collimator lenses (C), wire grid polarizer (P), one 2.5 mm TPX focusing lens (f), Mylar beam-splitter (S), beam dump(D), and a ZBD. The ZBD d.c. voltages are acquired with sweep delay of 500 ms and averaged for each BWO sweeper probe beam frequency.

Virginia Diode ZBD [9] with RF input in the range 110–170 GHz and responsivity $\sim$ 3.6 V/mW has linear RF power < -25 dBm with input power at 1 dB compression -20 dBm and NEP 2 pW/$\sqrt{Hz}$ is used for signal detection. Probe beam frequency is swept automatically using LabVIEW and sampling period is 500 ms.

Let us say E_0 is the incident amplitude on mirror/sample surface, then $E_0\rho$ is the reflected voltage registered by the detector, ρ being the mmW reflection coefficient of the material. We measure ZBD voltage response at various BWO mmW frequency and obtain a 30-sample average voltage using the DMM by directly feeding the ZBD DC output to it. The BWO is successively tuned to yield reflection signals off the first reflecting surface of mirror and N-GaN respectively. At first, a reference voltage spectrum is generated using the highly polished gold mirror reflector, and then, the mirror is replaced using the N-GaN on sapphire wafer and the sample reflection voltage spectrum is obtained likewise. The schematic of the experimental arrangement is shown below in Fig. 3.

For the data given here we have collected voltages that signify real part of reflection coefficient spectra at a frequency resolution 100 MHz. Following three steps are used for acquisition of reflection voltage response data:

1. Collect gold mirror reflected (E_0) spectral response of ZBD voltage by sweeping BWO between 107.35–165 GHz with resolution of 0.1 GHz and store data along with 10-sample standard deviation profile obtained from digital multimeter.
2. Mount N-GaN sample and rotate sample holder by 24.6° and perform alignment tests so that maximum power is received.
3. Replace gold mirror with sample as shown in position for N-GaN in Fig. 1 and repeat step 1 for collection of sample $E_0\rho$ (reflected voltage) data as function of frequency and corresponding standard deviation data from digital multimeter also using LabVIEW.

Ethics Statement

All authors declare that the authorship of this paper is legitimate. Authors declare that the data collected and the write up attached are original and properly cited and referenced. Authors have uploaded the raw dataset for users and provided quality flags for the data at frequencies that are physically not justified. Authors have no other conflicts of interest in this publication.

CRediT Author Statement

Biswadev Roy: Contributed to sample selection, experiment, conception, design, interpretation/analysis of the data and efforts for posting the data in public repository, writing-Reviewing and Editing the manuscript. Marvin H. Wu: Contributed to automated LabVIEW code development with BR, supervision of the data collection phase with important suggestions on data checks. Branislav Vlahovic: procured funds to buy samples and small supplies, liaised with funding agency, and helped in overall supervision of the laboratory facilities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

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Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.dib.2020.106419.

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