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Material and Device Engineering of Ga2O3 RF Electronics

MAN HOI WONG
UNIVERSITY OF MASSACHUSETTS
600 SUFFOLK ST STE 415
LOWELL, MA, 01854
USA

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Man Hoi Wong, Jian Li

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
UML performed numerical analyses to study the dynamics of hot carriers in ?-Ga2O3 HETs.
Such calculations transformed the microscale description of electron transport into a macroscopic description, providing a theoretical standard with which to compare experimental current–voltage (J–V) data while also enabling an appraisal of the HETs' high-frequency performance.
The transmission characteristics of an (AlxGa1–x)2O3 tunneling emitter barrier (Fig. 2)—chosen over a thermionic launcher to collimate the longitudinal momentum of injected carriers—was calculated by the quantum transmitting boundary method [2,3]. Band diagrams generated by a Schr?dinger–Poisson solver were used as inputs (Fig. 3). A (100) surface orientation was adopted to take advantage of its large conduction band offset (?EC) with Ga2O3 [4] and high Al incorporation [5]. The transmission coefficients (Fig. 4) thus obtained for various alloy compositions [x = 0.25 (typical), 0.5 (maximum reported [5]), 0.7 (theoretical maximum to maintain ?-phase)] and thicknesses (2–4 nm) were leveraged to calculate J–V curves based on thermionic field transport [6]. As can be seen in Figs. 5 and 6, higher emitter current (JE) requires thinner barriers or smaller ?EC, which increase the emitter–base capacitance (CBE) and thermionic leakage current, respectively. These tradeoffs may be overcome with a double-barrier resonant tunneling injector to achieve large JE while maintaining small CBE and low leakage.
2
Electrons incident at the collector barrier interface from the base experience quantummechanical reflection, which causes the transmission coefficient to vary within the longitudinal kinetic energies (Ez) occupied by the electron distribution (Fig. 7). An accurate simulation of this behavior is of interest for estimating the collector transfer ratio (?) and hence the current gain of HETs. As an illustration, the ? of an (Al0.5Ga0.5)2O3 collector as a function of the base–collector reverse bias was calculated by assuming a Gaussian distribution of Ez (Fig. 8). This bias-dependent momentum filtering characteristic of the collector barrier can be exploited for probing the energy spectrum of hot electrons in HETs.
Ga2O3 HETs can deliver a high output voltage with a relatively thin collector owing to the large critical field of (AlxGa1–x)2O3. Given that the collector thickness is constrained by breakdown and that the base delay is minimal, small-signal analysis shows that the intrinsic transit frequency (fT) of Ga2O3 HETs is limited by collector delay and CBE charging delay. For high ?JE ~ 500 kA/cm2, an fT beyond 500 GHz can be achieved.
The simulation results discussed above were presented at the 57th Workshop on Compound Semiconductor Materials and Devices (WOCSEMMAD 2022, Destin, FL, USA, Feb 20–23, 2022) and the 4th International Workshop on Gallium Oxide and Related Materials (IWGO-4, Nagano, Japan, Oct. 23–27, 2022, https://iwgo2022.org). A manuscript on "Quantum Transport in Ga2O3 Ballistic Electron Devices" is under preparation for submission to Applied Physics Letters. Based on the simulation results, epitaxial structures were designed and proposed to AFRL for extracting the barrier heights associated with the emitter–base and base–collector heterojunctions diodes of HETs and for characterizing current injection through (AlxGa1–x)2O3 tunneling barriers.

15. SUBJECT TERMS

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Material and Device Engineering of Ga_2O_3 RF Electronics
Award Number: FA2386-21-1-4071
Performance Period: 09/24/2021 to 09/23/2022

Background

The ultrawide-bandgap Ga_2O_3 semiconductor shows promise as the next leap in high-power radio-frequency (RF) electronics. Despite intensive pursuit of Ga_2O_3 RF transistors in recent years, ample research opportunities remain in both materials and devices to improve key performance metrics. This project aims at developing Ga_2O_3 hot-electron transistors (HETs) that harness non-equilibrium transport effects through heterojunction engineering to reduce carrier transit delay (**Fig. 1**). During device operation, electrons are injected over a large emitter barrier into a base transit region where they travel at a very high velocity toward a collector barrier that filters low-energy electrons. Designing the base with a thickness less than the hot-electron mean free path [1] serves to minimize scattering events and thus enable quasi-ballistic operation. These novel devices can theoretically exhibit superior high-frequency performance and will allow the first studies into the benefits of quasi-ballistic transport on the speed of Ga_2O_3 transistors. At the same time, the Ga_2O_3 HET is an effective spectroscopy tool for obtaining an in-depth understanding of hot-electron phenomena and ballistic transport physics that underlie device operation. Our project team consisting of UML (PI Wong) and NCKU (PI Li), together with collaborators at AFRL (Dr. Shin Mou, Dr. Tadj Asel), accomplished several deliverables in Year 1 of the performance period. The outcomes of this research promise next-generation Ga_2O_3 RF devices with significantly higher frequency and power-handling capacity than the current state-of-the-art.

UML Accomplishments

UML performed numerical analyses to study the dynamics of hot carriers in β-Ga_2O_3 HETs. Such calculations transformed the microscale description of electron transport into a macroscopic description, providing a theoretical standard with which to compare experimental current–voltage (J–V) data while also enabling an appraisal of the HETs' high-frequency performance.

The transmission characteristics of an $(Al_xGa_{1-x})_2O_3$ tunneling emitter barrier (**Fig. 2**)—chosen over a thermionic launcher to collimate the longitudinal momentum of injected carriers—was calculated by the quantum transmitting boundary method [2,3]. Band diagrams generated by a Schrödinger–Poisson solver were used as inputs (**Fig. 3**). A (100) surface orientation was adopted to take advantage of its large conduction band offset (ΔE_C) with Ga_2O_3 [4] and high Al incorporation [5]. The transmission coefficients (**Fig. 4**) thus obtained for various alloy compositions [x = 0.25 (typical), 0.5 (maximum reported [5]), 0.7 (theoretical maximum to maintain β-phase)] and thicknesses (2–4 nm) were leveraged to calculate J–V curves based on thermionic field transport [6]. As can be seen in **Figs. 5 and 6**, higher emitter current (J_E) requires thinner barriers or smaller ΔE_C, which increase the emitter–base capacitance (C_{BE}) and thermionic leakage current, respectively. These tradeoffs may be overcome with a double-barrier resonant tunneling injector to achieve large J_E while maintaining small C_{BE} and low leakage.

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Ga_2O_3 HETs can deliver a high output voltage with a relatively thin collector owing to the large critical field of $(Al_xGa_{1-x})_2O_3$. Given that the collector thickness is constrained by breakdown and that the base delay is minimal, small-signal analysis shows that the intrinsic transit frequency (f_T) of Ga_2O_3 HETs is limited by collector delay and C_{BE} charging delay. For high $\alpha J_E \sim 500$ kA/cm^2, an f_T beyond 500 GHz can be achieved.

The simulation results discussed above were presented at the 57th Workshop on Compound Semiconductor Materials and Devices (WOCSEMMAD 2022, Destin, FL, USA, Feb 20–23, 2022) and the 4th International Workshop on Gallium Oxide and Related Materials (IWGO-4, Nagano, Japan, Oct. 23–27, 2022, https://iwgo2022.org). A manuscript on "Quantum Transport in Ga_2O_3 Ballistic Electron Devices" is under preparation for submission to Applied Physics Letters. Based on the simulation results, epitaxial structures were designed and proposed to AFRL for extracting the barrier heights associated with the emitter–base and base–collector heterojunctions diodes of HETs and for characterizing current injection through $(Al_xGa_{1-x})_2O_3$ tunneling barriers.

NCKU Accomplishments

NCKU conducted capacitance-voltage measurement and capacitance based spectroscopic characterization on two-terminal Schottky-junction-like devices on thick Ga_2O_3 layers and other gallium-based wide bandgap semiconductor compounds to investigate material physics subject of the electrical properties, especially *n*-type doping and defects. Other materials and testing structures such as uniform-composition $(Al_xGa_{1-x})_2O_3$ alloys and heterostructures consisting of a combination of Ga_2O_3 and $(Al_xGa_{1-x})_2O_3$ were not available during the period of performance. Additionally, NCKU's work on "Thin-Film Temperature Sensors Based on LPD-Fabricated β-Ga_2O_3 Schottky Diodes" was partly supported by this project and published in AIP Advances.

NCKU–UML Joint Accomplishments

NCKU and UML jointly developed the Arrhenius transformation and matching (ATM) method to extract activation energy and attempt-to-escape frequency of the nitrogen-related defect (E1) in GaAsN from admittance spectroscopy measurements taken at various temperature and electric field. The ATM method is equivalent to the conventional Arrhenius plot and line-fitting (APL) method for Arrhenius processes with temperature-independent E_a and ν_0 (e.g., E1 in a low electric field and at high temperatures) and advantageous for non–Arrhenius processes with temperature-dependent E_a and ν_0 (e.g., E1 in a high electric field and at low temperatures), where the APL method is not reliable. The ATM method enables a detailed account on how E_a evolves with the

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temperature and the electric field in a continuously varying experimental space (**Fig. 9**), which is not possible with the APL method. The evolution of carrier emission behaviors from the E1 defect and a neighboring E2 defect provides experimental evidence of field-induced metastability possibly due to the interaction of two defects with close atomic origins or spatial locations. This NCKU–UML joint manuscript was published in Thin Solid Films.

NCKU–AFRL–UML Joint Accomplishments

NCKU–AFRL–UML jointly investigated a defect in the β-Ga_2O_3 substrate material from capacitance transients. The defect ~0.8 eV below the conduction band edge of β-Ga_2O_3 wide bandgap semiconductor is investigated using the matched Arrhenius-equation projection technique that offers substantial improvement over the conventional deep level transient spectroscopy technique. An experimental technique is developed to extract activation energy E_a and attempt-to-escape frequency v_0 of defects bypassing both the rate-window treatment and the Arrhenius plot. Only the raw capacitance transients in the time domain are needed with this technique (**Fig. 10**). The capacitance transients are projected between the temperature and time domains, as well as to the E_a and v_0 domains. Extraction of E_a and v_0 is accomplished by matching the projected and experimental capacitance transients to each other. NCKU–AFRL–UML jointly presented the work on "Advanced Defect Characterization in β-Ga_2O_3 without the Arrhenius Plot" at the 5th U.S. Gallium Oxide Workshop (GOX 2022, Washington D.C., August 7–10, 2022, https://gox2022.avs.org/). In addition, an NCKU-AFRL-UML joint manuscript was published in the Journal of Vacuum Science and Technology B and chosen as an Editor's Pick paper.

Others

Due to the short performance period and unexpected resignment of PI Jian Li from NCKU (effective 07/31/2022), not all the budgeted funds have been used. Below is a breakdown of NCKU's expense items. Since UML implemented a strict invoice-after-expense policy for the NCKU subaward, there is no need to return funds to UML.

Table I. Expense summary of NCKU

CATEGORY	a. Personnel	b. Fringe Benefits	c. Travel	d. Equipment	e. Supplies	f. Total Direct Costs	g. Total Indirect Charges	h. Total Costs
Budget	$19,098	$0	$3,621	$40,297	$5,684	$68,700	$17,175	$85,875
Expense	$11,929	$0	$0	$38,786	$4,588	$55,483	$9,649	$64,952

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1. S. Marcinkevičius *et al.*, APL **118**, 242101 (2021).
2. C. S. Lent *et al.*, JAP **67**, 6353 (1990).
3. C. L. Fernando *et al.*, JAP **86**, 2881 (1994).
4. A. F. M. A. U. Bhuiyan *et al.*, JVST A **39**, 063207 (2021).
5. A. F. M. A. U. Bhuiyan *et al.*, Cryst. Growth Des. **20**, 6722 (2020).
6. R. Tsu *et al.*, APL **22**, 562 (1973).

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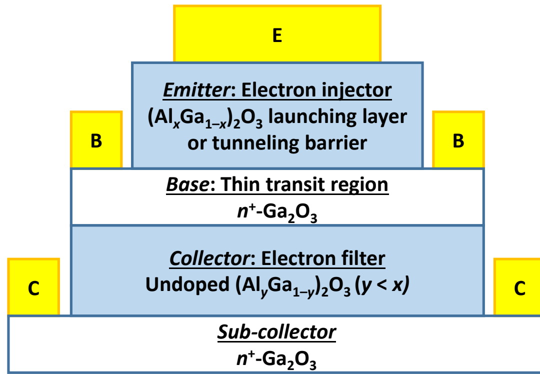

Fig. 1. Layer structure of a Ga_2O_3 HET.

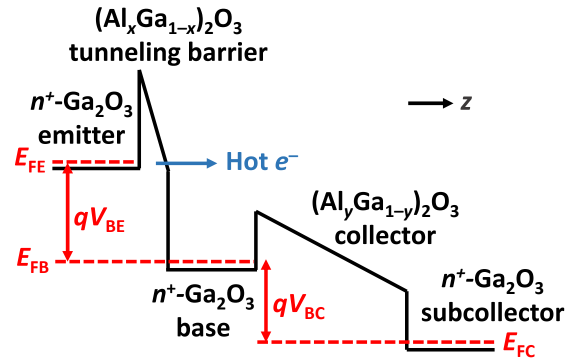

Fig. 2. A Ga_2O_3 HET with an $(Al_xGa_{1-x})_2O_3$ tunneling emitter barrier. The base–emitter forward biasing voltage and base–collector reverse biasing voltage are V_{BE} and V_{BC}, respectively.

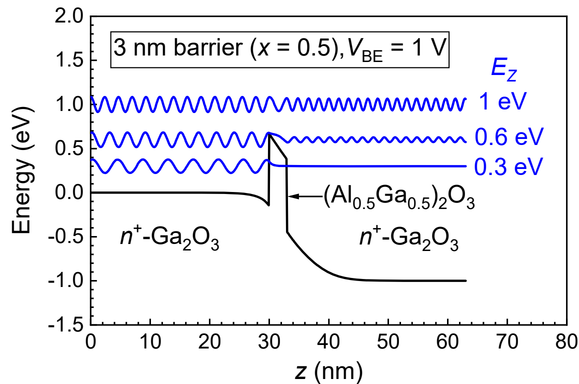

Fig. 3. Emitter barrier conduction band diagram for V_{BE} = 1 V. The wavefunctions of electrons with incoming E_z of 0.3, 0.6, and 1 eV are also illustrated.

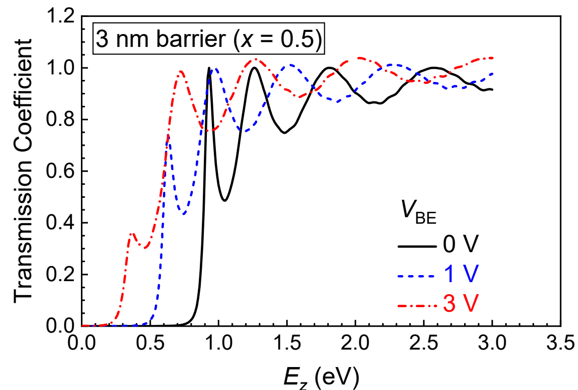

Fig. 4. Bias-dependent transmission coefficients for the emitter barrier in Fig. 3 at different V_{BE}. Quantum interference effects are manifest.

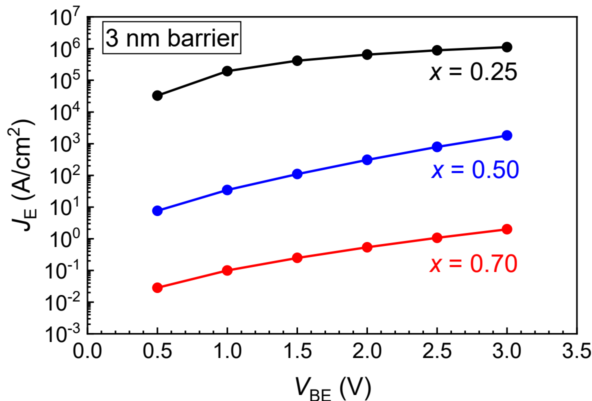

Fig. 5. Injected hot-electron J_E vs. V_{BE} for a 3-nm-thick $(Al_xGa_{1-x})_2O_3$ tunneling barrier with varied x. Smaller ΔE_C due to lower x enhances thermionic field emission and hence the total current.

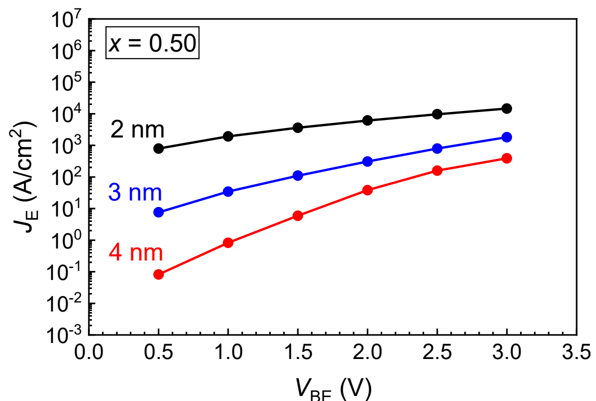

Fig. 6. Injected hot-electron J_E vs. V_{BE} for an $(Al_{0.5}Ga_{0.5})_2O_3$ tunneling barrier with varied thicknesses. Thinner barriers enhance tunneling and hence the total current.

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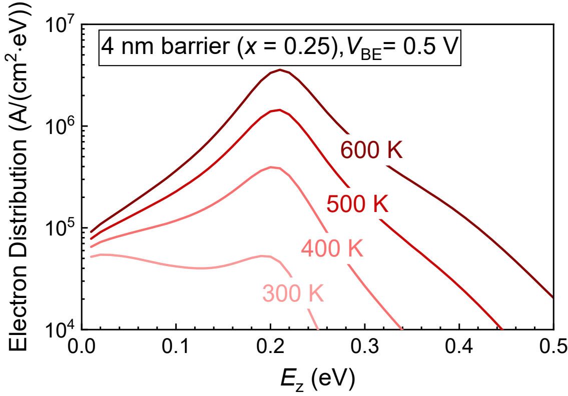

Fig. 7. E_z distribution of hot electrons emitted from a 4-nm-thick $(Al_{0.25}Ga_{0.75})_2O_3$ tunneling barrier at a forward bias of 0.5 V. These curves indicate the relative contribution from electrons with different E_z to the total current. For a given temperature, the electron concentration decreases with E_z while the transmission probability increases, resulting in local maxima near $E_z = 0.2$ eV.

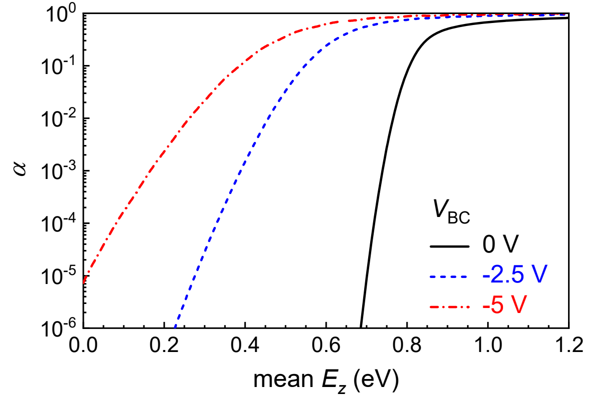

Fig. 8. Bias-dependent collector transfer ratios α for a Gaussian packet of electrons with mean energy E_z (determined by the emitter injection energy and the base width) upon arrival at an $(Al_{0.5}Ga_{0.5})_2O_3$ collector barrier.

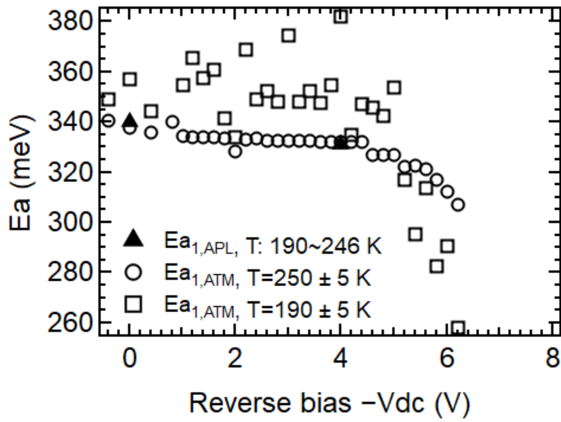

Fig. 9. E-field dependence of E_a of a defect in GaAsN.

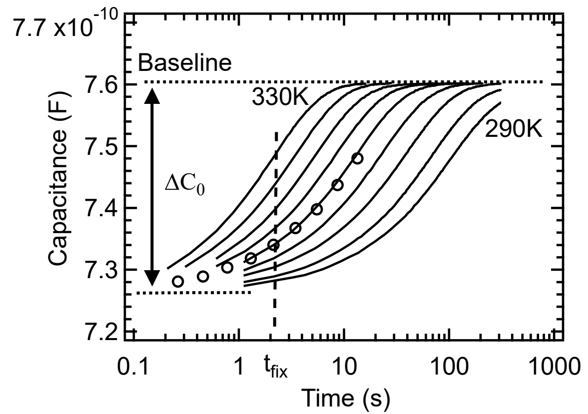

Fig. 10. Capacitance transients extraction of E_a and v_0 of a defect in β-Ga_2O_3.

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METRICS COLLECTION FOR:

MATERIAL AND DEVICE ENGINEERING OF GA_2O_3 RF ELECTRONICS

USA	Taiwan
Man Hoi Wong	**Jian V. Li**
University of Massachusetts Lowell	**National Cheng Kung University**

PATENTS / INDUSTRY / USAF / DOD RELATIONSHIPS

- Li transitioned to AFRL in Dayton, Ohio, in August 2022.
- Wong, who transitioned to a new position in Hong Kong in September 2022, had planned a visit to AFRL in November 2022 but the trip was cancelled due to security clearance issues created by newly imposed US export controls on Ga_2O_3.

[Team Projects] TEAM COLLABORATION SYNERGY HIGHLIGHTS

- Seven journal and conference publications were supported by this grant, four of which were joint publications (see table in Publications).
- NCKU conducted capacitance measurement on a Ga_2O_3 Schottky sample from UML.
- Ten Ga_2O_3 substrates were provided to AFRL for MBE growth of $(Al_xGa_{1-x})_2O_3/Ga_2O_3$ heterostructures for device studies and advanced defect characterizations.

AWARDS or FOLLOW-ON PROJECTS ENABLED

- During the Year 1 performance period, Wong was concurrently funded by the AFOSR on the "MURI: Gallium Oxide Materials Science and Engineering (GAME)" program (Award no.: FA9550-18-1-0479, $7.5M). The overall objective of the MURI was to investigate the fundamental electronic, optical, and thermal properties of Ga_2O_3 with emphases on growth studies, structure–property correlations, and heterostructure design. The results generated from the AOARD grant were synergistic with the discoveries of the MURI.

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PUBLICATIONS

(Issued, in press, planned in peer-reviewed journals, and in non-peer-reviewed journals)

Bibliometric Entry with any Typical Format (Author, Title, Journal, Volume, Date).	*Digital Object Identify (DoI) Link* *arXiv:16XX.YYYY Link*	*Citations from Google Scholar or Web Of Science*
(NCKU) S. Paul, T.-S. Chen, M.-P. Houng, and J. V. Li, "Thin-film temperature sensors based on LPD-fabricated β-Ga_2O_3 Schottky diodes," AIP Adv. **12**, 055314 (2022).	https://doi.org/10.1063/5.0090723	0 (as of Dec 2022)
(NCKU–UML) J. V. Li and M. H. Wong, "Investigation of electric field effect on defects in GaAsN by admittance spectroscopy," Thin Solid Films **758**, 139422 (2022).	https://doi.org/10.1016/j.tsf.2022.139422	0 (as of Dec 2022)
(NCKU–AFRL–UML) J. V. Li, A. T. Neal, S. Mou, and M. H. Wong, "Investigation of a defect in the β-Ga_2O_3 substrate material from capacitance transients," J. Vac. Sci. Technol. B **40**, 064001 (2022). **[Editor's Pick]**	https://doi.org/10.1116/6.0002045	0 (as of Dec 2022)
(UML) N. Hossain and M. H. Wong, "Gallium oxide hot electron devices," 57th Workshop on Compound Semiconductor Materials and Devices (WOCSEMMAD 2022), Destin, FL, USA, Feb. 20–23, 2022.	n/a	n/a
(NCKU–AFRL–UML) J. V. Li, A. T. Neal, S. Mou, and M. H. Wong, "Advanced Defect Characterization in β-Ga_2O_3 without the Arrhenius Plot", 5th U.S. Gallium Oxide Workshop (GOX 2022), Washington D.C., USA, August 7–10, 2022.	https://gox2022.avs.org/	n/a
(UML) N. Hossain and M. H. Wong, "Quantum Transport in Ga_2O_3 Ballistic Electron Devices," 4th International Workshop on Gallium Oxide and Related Materials (IWGO-4), Nagano, Japan, Oct. 23–27, 2022.	https://iwgo2022.org	n/a
(UML–NCKU–AFRL) N. Hossain, J. V. Li, S. Mou, and M. H. Wong, "Quantum Transport in Ga_2O_3 Ballistic Electron Devices," planned submission to Appl. Phys. Lett.	n/a	n/a

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