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TECHNICAL REPORT

Radiation Effects in High-k Gate Dielectrics on III-V Semiconductors

October 2018

HDTRA1-10-1-0042

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14. ABSTRACT
This research project was conducted to further the fundamental understanding of mechanisms of radiation effects in high-k gate dielectrics on 111-V semiconductors, such as GaAs, lnGaAs, lnAs, GaN, AIN, and GaAIN etc. with an emphasis on the the total ionization dose (TIO) effects on the generation mechanisms of electrically active defects in the gate dielectrics and at the interfaces that cause radiation-induced threshold voltage shift, degraded transconductance, increased leakagecurrent, and decreased dielectric breakdown strength. The most significant results, including those related to TIO-induced defects in the gate stacks and their effects on device performance and reliability are reported.

15. SUBJECT TERMS
Ionizing Radiation Effects; TIO Effects; Mechanisms; Gate Stacks; 111-V Semiconductors; CMOS Transistors; HEMTs

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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement*

U.S. Customary Units	Multiply by → / ← Divide by†		International Units
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^{3}$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m^3)
cubic foot (ft^3)	2.831 685	$\times 10^{-2}$	cubic meter (m^3)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
unified atomic mass unit (amu)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846	$\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
pound-force (lbf avoirdupois)	4.448 222		newton (N)
Energy/Work/Power			
electron volt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kt) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^{3}$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Pressure			
atmosphere (atm)	1.013 250	$\times 10^{5}$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^{3}$	pascal (Pa)
Temperature			
degree Fahrenheit (°F)	$[T(^{o}F) - 32]/1.8$		degree Celsius (°C)
degree Fahrenheit (°F)	$[T(^{o}F) + 459.67]/1.8$		kelvin (K)
Radiation			
curie (Ci) [activity of radionuclides]	3.7	$\times 10^{10}$	per second (s^{-1}) [becquerel (Bq)]
roentgen (R) [air exposure]	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg^{-1})
rad [absorbed dose]	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1}) [gray (Gy)]
rem [equivalent and effective dose]	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1}) [sievert (Sv)]

*Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.

†Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

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What are the major goals of the project?

The major goals are to further the fundamental understanding of mechanisms of radiation effects in high-k gate dielectrics on III-V semiconductors, such as GaAs, InGaAs, InAs, GaN, AlN, and GaAlN etc. by conducting experimental and theoretical studies; in particular, the total dose effects on the generation mechanisms of electrically active defects in the gate dielectrics and at the interfaces that cause radiation-induced threshold voltage shift, degraded transconductance, increased leakage current, and decreased dielectric breakdown strength

What was accomplished under these goals?

A. **Major Activities**:

- Study of hole trapping in AlGaN/GaN HEMTs & MOSHEMTs under X-ray irradiation
- IETS study of generation and transformation of electron traps in AlGaN/GaN HEMTs upon X-ray irradiation and subsequent post-irradiation room-temperature anneal
- Comparative study of radiation effects in planar and nanowire structured high-k/InGaAs MOSFETs
- Comparative study of radiation effects in state-of-the-art planar and nanowire structured high-k/InGaAs MOSFETs
- IETS study of generation and transformation of electron traps in AlGaN/GaN HEMTs upon X-ray irradiation and subsequent post-irradiation room-temperature storage.

B. **Specific Objectives**:

- Understanding of charge trapping mechanisms in AlGaN/GaN HEMTs and high-k gated MOSHEMTs, as well as their effects on radiation hardness of the devices.
- Understanding of the impact of total-dose X-ray irradiation on electron trapping and on the reliability of AlGaN/GaN HEMT devices
- Evaluation of device performance and reliability of state-of-the-art high-k/InGaAs nanowire MOSFETs
- Understanding of the impact of nanowire dimension, device process variation, and bias condition during x-ray irradiation on device performance and reliability of nanowire high-k/InGaAs MOSFETs.
- Understanding of the mechanism(s) responsible for the trap energy shift during post-irradiation room temperature storage, and corresponding effects on the long term reliability of AlGaN/GaN HEMT devices

C. **Significant Results**:

- Carried out studies of radiation effects on Au/Al_2O_3/ $In_{0.53}Ga_{0.47}As$ MOS capacitors with both conventional electrical measurements and IETS. The IETS data not only revealed radiation-induced generation of interface and oxide traps, but also uncovered the changes in energy and in spatial location of the oxide traps.
- Studied the total-dose radiation effects in AlGaN/GaN MOS-HEMTs grown on Si substrates, which primarily exhibited two separate kinds of V_{th} shifts under 10 keV X-ray irradiation: a fast shift at low doses [< 3 krad(SiO_2)] for devices with or without a high-κ gate dielectric, and additional charge trapping in devices with high-κ gate dielectrics for doses up to at least 2 Mrad(SiO_2). The fast V_{th} shift is attributed to bulk hole traps in the AlGaN layers. The hole trapping in the gate dielectric layer is a strong function of layer material, annealing temperature, and applied radiation bias. The relatively small shifts observed in MOS-HEMTs with HfO_2 layers annealed at 500 ºC are especially encouraging for further development. IETS (Inelastic Electron Tunneling Spectroscopy) measurements revealed radiation-induced trap features, which appear to shift in energy during room-temperature storage. The responsible mechanism is being investigated.
- Continued investigation on the impact of total-dose x-ray irradiation on electron trapping and the reliability of AlGaN/GaN HEMT devices has pointed to the conclusion that microstructural defective region near AlGaN/GaN interface is accountable for the formation of a spatially broad trap band; weak bonds in this region are more susceptible to x-ray irradiation, resulting in stronger IETS trap feature; During post-radiation room temperature storage (when the gate is floating), electrons from 2DEG gradually fill these traps, causing

the trap energy to shift (⍰V_{trp}) over a long time period, which may raise a concern of device reliability.

- Studied the Total Irradiation Dose (TID) effects on InGaAs based planer and nanowire (NW) gate-all-around (GAA) MOSFETs. The latter have various NW thicknesses, with or without forming gas (FG) annealing treatment during device fabrication. Our primary results can be summarized as the following: (1) nanowire devices exhibit much smaller TID effects than their planer counterparts; (2) the thinner the nanowire, the better the radiation hardness, in terms of the smaller negative threshold voltage shifts (ΔV_{th}) and faster ΔV_{th} recovery during post-irradiation room temperature storage; (3) devices which received post-metal FG annealing during device fabrication exhibit improved radiation hardness than those without FG treatment; (4) Bias condition during x-ray irradiation has strong impact on device radiation hardness – negative gate bias (*e.g.* -0.5V below V_{th}) always results in greater negative threshold voltage shifts than when all the terminals are grounded. Our low frequency (*1/f*) noise data suggest a strong correlation between the oxide trap density and the degree of the x-ray induced threshold voltage shift, indicating that hole trapping at the trap sites (both the existing and radiation generated oxide traps) is the dominating mechanism accountable for device radiation hardness.

The aforementioned results are shown in more detail in the next session.

D. **Technical Data**:

I. **Hole trapping in AlGaN/GaN HEMTs & MOS-HEMTs**

As seen in both Figs. 1a & 1b, X-ray irradiation causes negative shifts of the Id-Vg curve in both samples, indicative of net hole trapping. The major difference is that, for HEMT, the Id-Vg shift saturates after about 3krad of radiation, while for the MOS-HEMT the shift continues to increase up to 1Mrad of radiation.

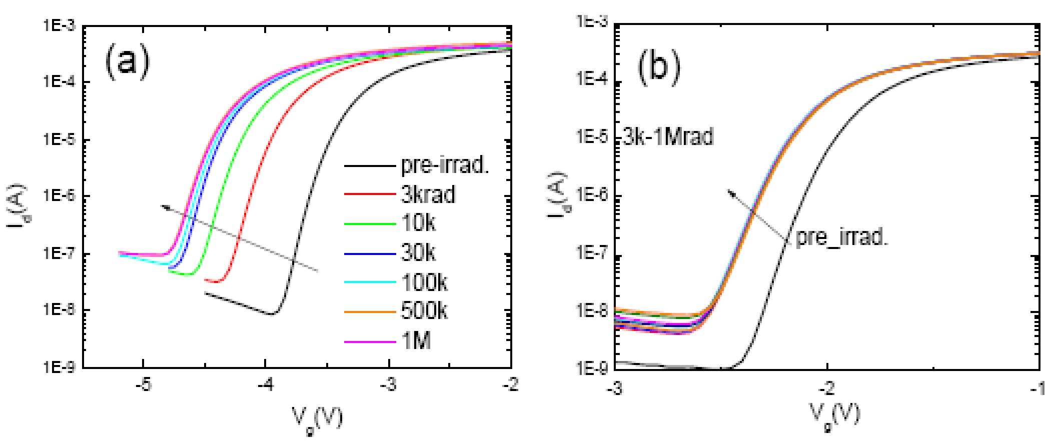
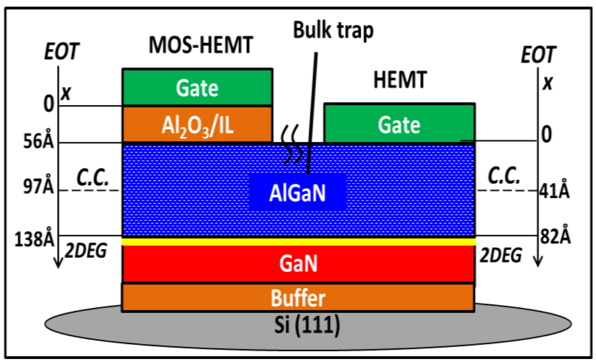


Fig. 1, I_d-V_g curve shifts with X-ray radiation up to 1Mrad (SiO_2) for (a) a MOS-HEMT, and (b) HEMT

Our analysis indicates that the initial I_d-V_g shift (refer to Fig.1b) is caused by the radiation-induced holes trapped in the AlGaN layer. Further shifts of the I_d-V_g observed in the MOS-HEMT (refer to Fig.1a) arise from the holes trapped in the gate dielectric. The results of our analysis are presented in Figure 2b, based on the device structures shown in Fig.2a. Assuming a uniform distribution, the charge centroid of the trapped holes in AlGaN should be located at 97Å (EOT) away from the gate metal (x=0) for MOS-HEMT, and 41Å (EOT) for HEMT. In Fig.2b, the red and black curves represent ΔV_{th} during the initial X-ray exposure up to 3Krad for the MOS-HEMT and the HEMT, respectively. It is found that the ΔV_{th} (red) vs. ΔV_{th} (black) exactly follows the ratio of 97/41 as evidenced by the nearly perfect overlapping of the black curve & the resulting blue curve.



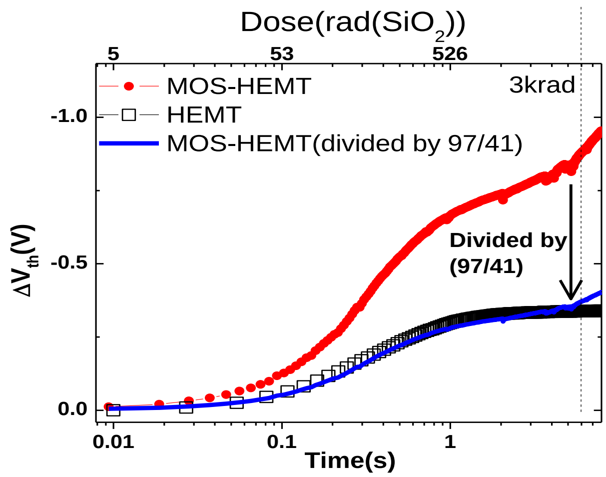


Fig. 2a, MOS-HEMT & HEMT structures under study, where the equivalent oxide thickness (EOT) of gate dielectric and AlGaN, as well as the charge centroid in the AlGaN are marked on the sides.

Fig. 2b, ΔV_{th} as a function of X-ray dose (or time) for a MOS-HEMT & a HEMT up to 3Krad X-ray exposure. V_{th} was extracted by sampling drain current at fixed V_g

With a longer X-ray exposure, Figure 3 shows that the ΔV_{th}~ t curve (blue) of the MOS-HEMT consists of two components: (1) the initial V_{th} shift caused by trapped holes in AlGaN (black) and (2) additional shift caused by trapped holes in the gate Al_2O_3(red). Furthermore, ΔV_{th} of either components is approximately linearly proportional to the x-ray dose; and the capture cross sections of traps in AlGaN seem greater than those in Al_2O_3, resulting in faster hole trapping in AlGaN.

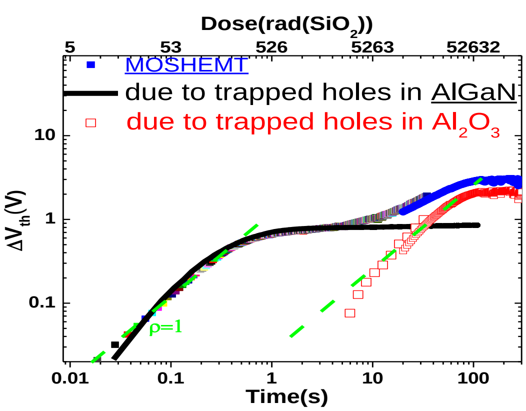


Fig. 3, De-convolution of the ΔV_{th}–t curve of the MESHEMT reveals ΔV_{th} arising from trapped holes in AlGaN (black curve) and in the gate Al_2O_3 (red curve).

The following results suggest that one can use the saturation value of ΔV_{th} as a measure of the quality & radiation hardness of HEMT structures. As exemplified in Fig. 4, under the same radiation condition, two HEMT structures from two different commercial venders exhibit significantly different radiation hardness, due to an order of magnitude different trapped hole densities. Also seen in figure 4 is that the radiation response of the AlGaN/GaN HEMT structure grown on SiC (blue dashed line) is superior to that grown on Si substrate.

The saturation value of ΔV_{th} could also be used to evaluate the quality and effects of device processing on the radiation responses of gate dielectrics. Figure 5 shows density of the trapped holes as a function of X-ray dose for HfO_2 and Al_2O_3, each received 400C & 500C post-metal-anneals. Evidently, with 500C PMA, HfO_2- gated MOS-HEMT exhibits negligible ΔV_{th} up to 2Mrad, indicating hole trap density less than low-$10^{11}/cm^2$, while Al_2O_3 appears to be in inferior quality with an order of magnitude higher hole trap density.

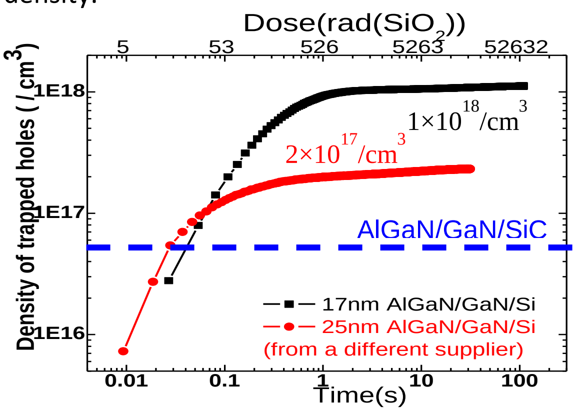


Fig. 4 Densities of trapped holes in AlGaN as functions of radiation dose (time) for two HEMT structures from two commercial venders

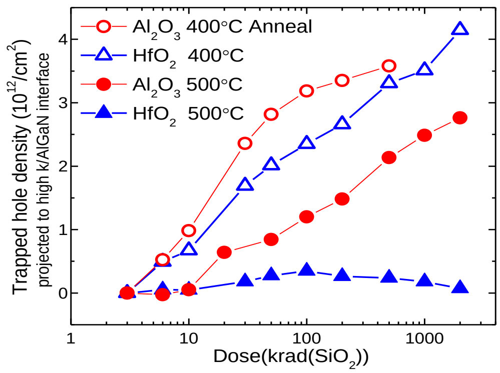


Fig. 5, Densities of trapped holes as functions of radiation dose in HfO_2 and Al_2O_3, respectively. Both
1 dielectrics received 400C and 500C anneals.

III. Transformation in energy and position upon post-irradation room temperature anneal

We have studied the IETS spectra of the AlGaN/GaN HEMT structures both before and after various doses of X-ray irradiation, as well as after room-subsequent temperature anneal. While the radiation-induced damage for the radiation doses used in this study (<1.5 Mrad), is hardly detectable by the use of the conventional DC-IV measurements (data not shown) , it becomes strongly evident in the IETS -the 2^{nd} derivative of the I-V curve arising from electron tunneling through the gate barrier. The most prominent changes in the IETS spectra after the X-ray exposure is the appearance of a large & broad “down-up-down” feature approximately in the gate voltage range of -0.3V to -0.5 V (refer to Figs.6b & c). It seems that a related feature can be vaguely seen in the virgin sample (refer to box in Fig.6a), but it is much weaker and may be easily overlooked. The IETS spectra in Figs.6b&c indicate that a high density of electron traps in the AlGaN layer is generated by X-ray irradiation, and the energy levels of these traps are in the range (or a band) of 0.3-0.5eV above the GaN conduction band minimum.

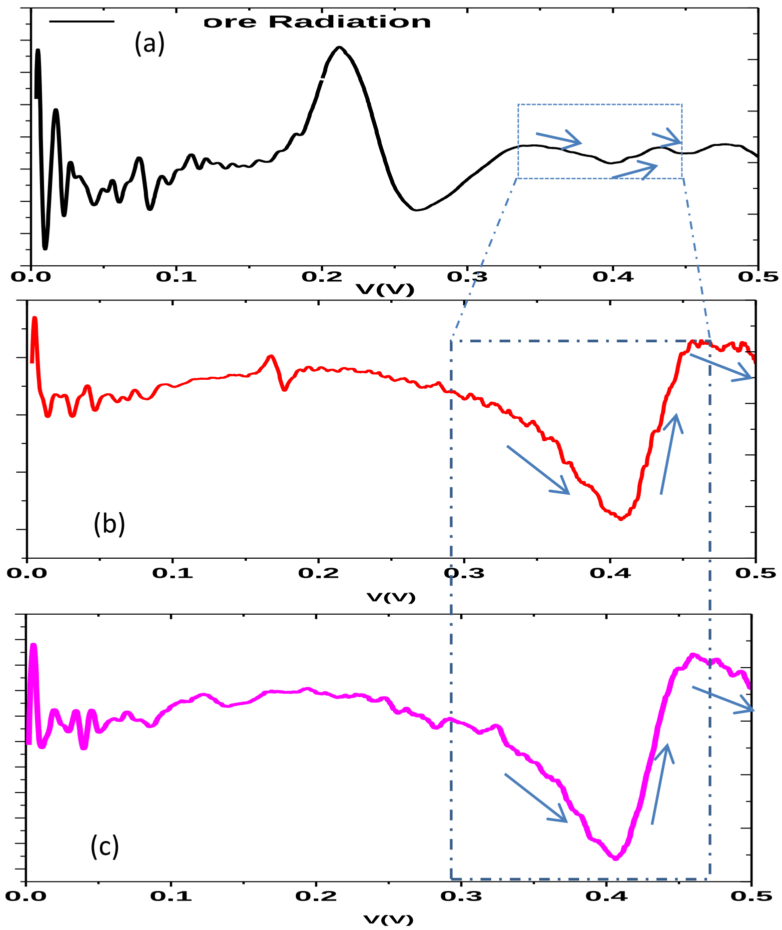


Fig. 6, IETS taken on a AlGaN/GaN HEMT (a) as-processed; (b) after 500Krad X-ray radiation; and (c) after 1.5Mrad radiation.. A broad "down-up-down" feature in the highlighted box indicates X-ray induced electron trapping events in AlGaN

It is interesting to note that the centroid of the trap energy band tends to shift upwards during the post-irradiation room temperature storage. Fig. 7 shows an example of such shift after 700 hours storage for the sample that received 1.5Mrad X-ray irradiation. The mechanism behind such trap energy/spatial transformation is under investigation.

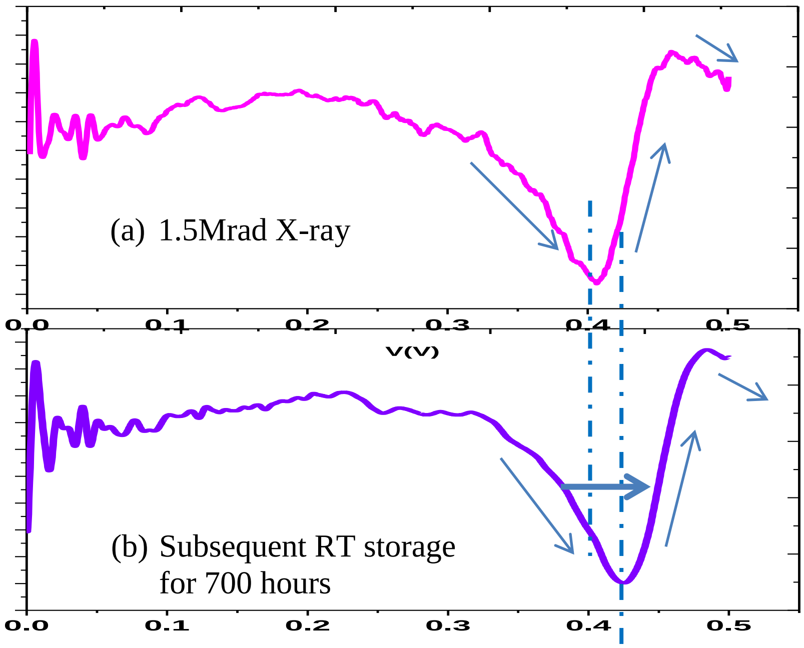


Fig. 7, Energy levels of the electron traps tend to shift upwards away from the GaN conduction band minimum. (a) IETS collected after 1.5Mrad X-ray irradiation on an AlGaN/GaN HEMT; (b) IETS of the same device stored at room temperature for 700 hours after X-ray exposure

IV. **Hole trapping in InGaAs NW GAA MOSFETs**

Schematic diagrams and channel cross section of the devices under study are shown in Figs. 8(a), (b) and (c). Both the InGaAs NW-GAA MOSFETs and the control InGaAs planar devices have 5nm ALD Al_2O_3 as the gate dielectric. Figures 9(a) and (b) show I_d-V_g characteristics of planar and NW GAA devices for x-ray doses up to 1 Mrad(SiO_2). Figure 10 compares radiation-induced V_{th} shifts (ΔV_{th}) between these two types of devices. Negative V_{th} shifts are observed after irradiation, consistent with net hole trapping in the Al_2O_3 layers; the NW GAA devices in Fig. 9(b) exhibit much smaller threshold voltage shift (ΔV_{th} ~15 mV) as compared with the planar devices in Fig. 9(a) (~350 mV), likely due to enhanced gate control in the NW GAA devices. The measured peak G_m and the sub-threshold swing (SS) of both types of devices remain almost unchanged during and after irradiation (data not shown), suggesting that 1 Mrad(SiO_2) radiation does not cause significant degradation in mobility or interface properties for both types of devices.

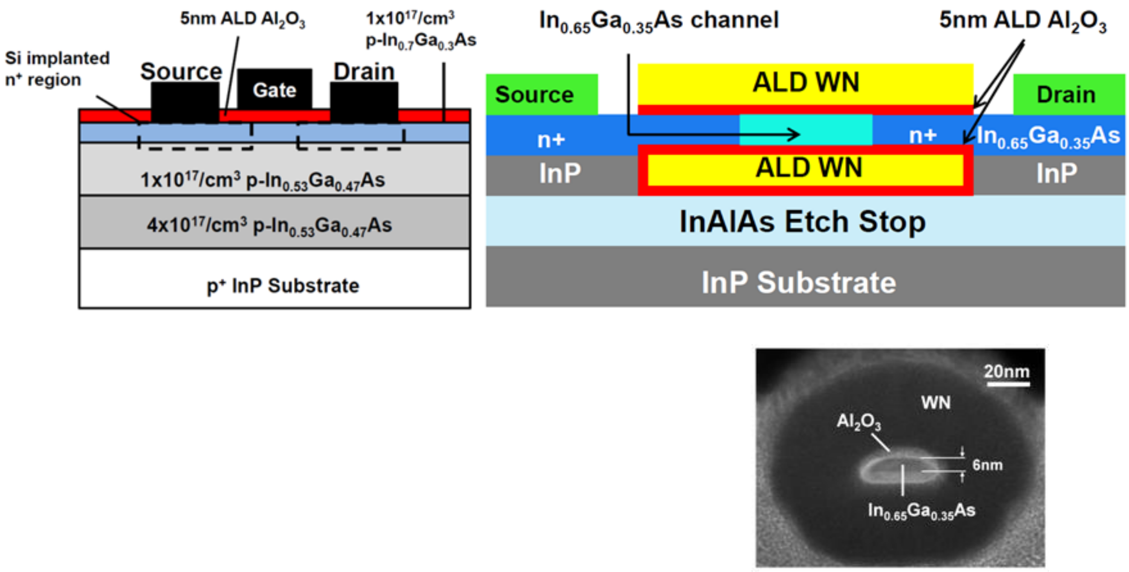


Fig. 8, Schematic diagrams of (a) planar InGaAs MOSFETs; (b) lateral view and (c) cross-sectional TEM of InGaAs ultra-thin nanowire gate-all-around MOSFETs.

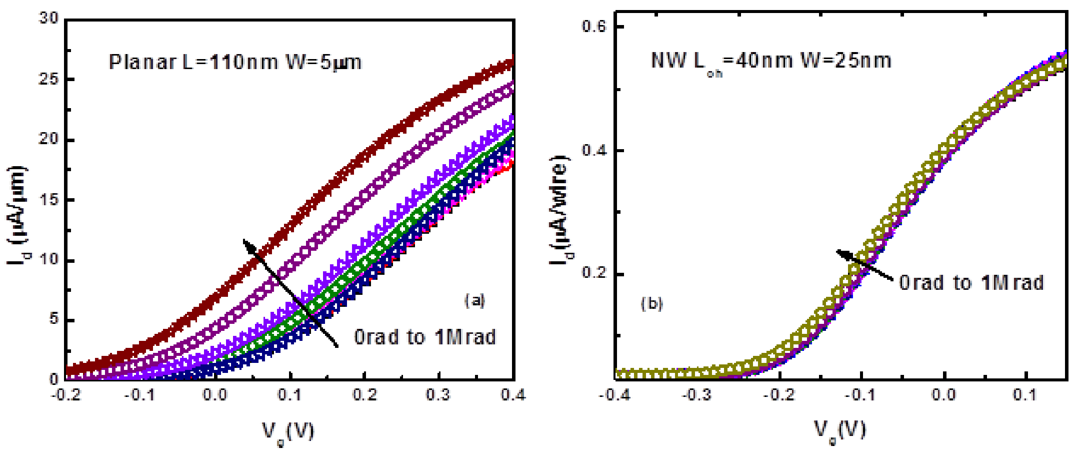


Fig. 9, I_d-V_g curve shifts with increasing radiation dose up to 1Mrad (SiO_2) for (a) planar and (b) NW InGaAs MOSFETs with all terminals grounded during irradiation

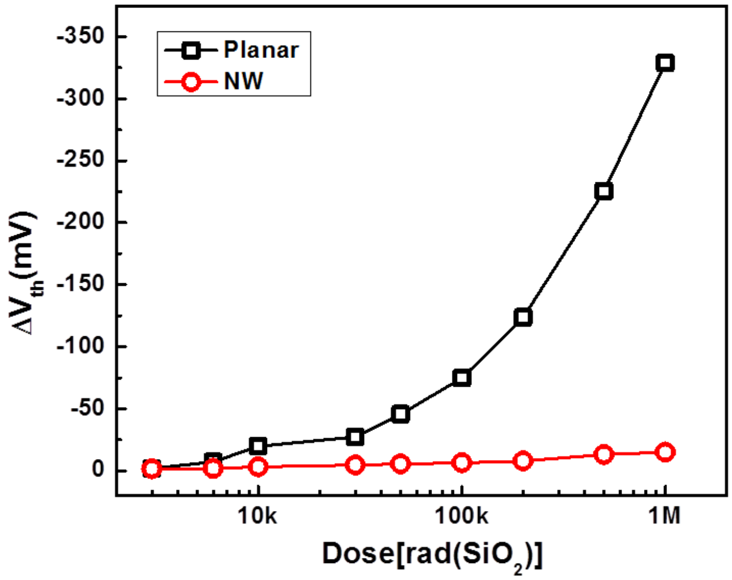


Fig. 10, Threshold voltage shifts (ΔV_{th}) as functions of x-ray dose for a planar (black) and an NW (red) InGaAs MOSFETs. Both devices show negative V_{th} shifts indicating net hole trapping

V. <u>Factors that affect radiation hardness of InGaAs NW GAA MOSFETs</u>

a) NW thickness

Figure 11 shows ΔV_{th} as a function of x-ray dose for device A (NW thickness ~10nm) and B (NW thickness ~20nm), respectively. Also shown in Fig. 11 are the post-irradiation ΔV_{th} recovery during room temperature storage. It is clearly seen that thinner NW (device A) gives rise to smaller V_{th} shift than thicker NW (device B). Also, V_{th} recovers to its pre-irradiation level (*i.e.* ΔV_{th} ~ 0) shortly after room temperature storage for device A, whereas for device B V_{th} recovery tends to level out after 100min room temperture storage.

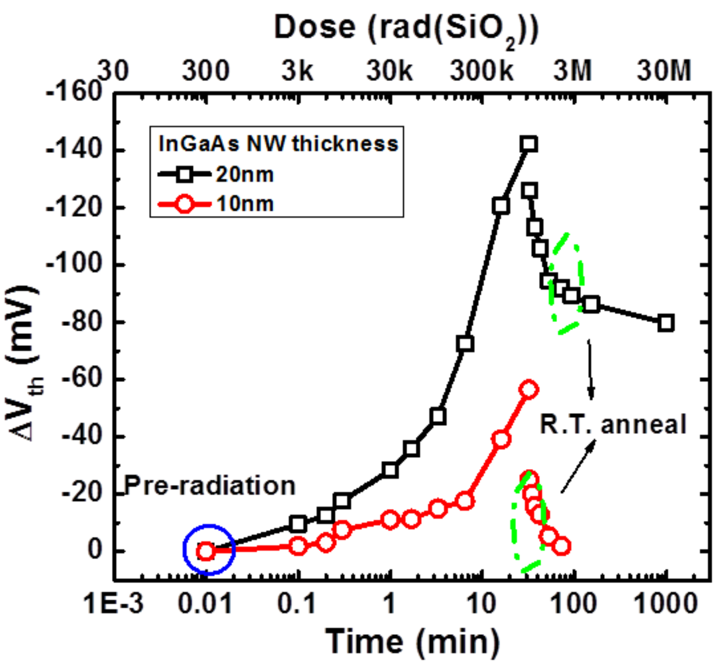


Fig. 11, Threshold voltage shifts as functions of time duration of x-ray exposure for NW GAA InGaAs MOSFETs with 20nm (black) and 10 nm (red) channel. Also shown is ΔV_{th} recovery after 1Mrad of radiation at room temperature.

a) Process variation

Figure 12 (a) compares TID effects on NW GAA MOSFETs with and without post-metal forming gas anneal (FGA). Devices which received FGA exhibit smaller ΔV_{th} than those without FGA. 1/f nosie measurements (Fig. 12b) indicate that for both types of devices the S_{Id}/I_d^2 -I_d curves fit the number fluctuation model, meaning that the current noise spectral density level is proportional to the oxide trap density. Therefore, by comparing the level of current noise spectral density one can tell that the oxide trap density in FGA treated device is much smaller than that in non-FGA treated device, causing fewer holes (generated by x-ray irradiation) trapped in the oxide, resulting in less threshold voltage shift.

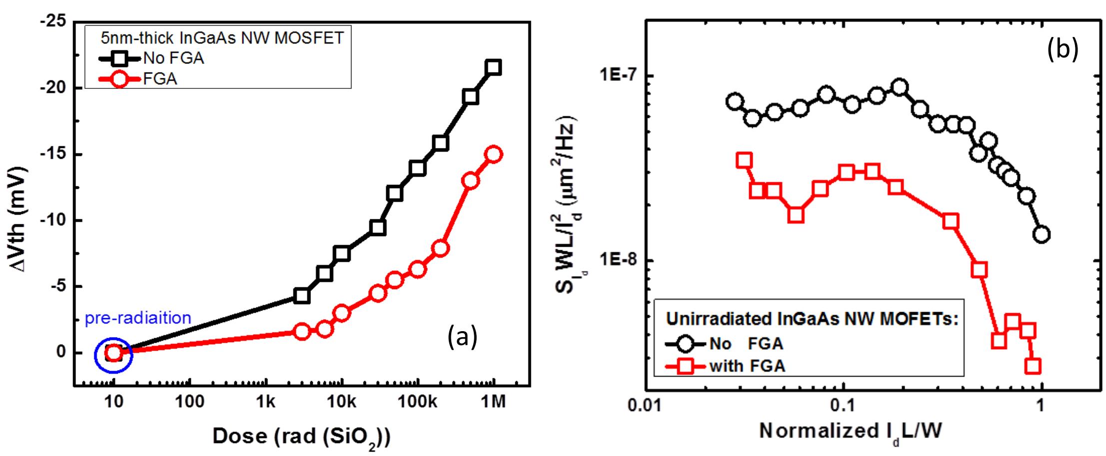


Fig 12, (a) ΔV_{th} as functions of radiation dose of InGaAs NW MOSFETs with (red) and without (black) FGA; (b) *1/f* nosie measurements show higher oxide trap density for the device without FGA than device with FGA

b) Gate bias during x-ray irradiation

Figure 13 (a) shows ΔV_{th} as functions of radiation dose in NW GAA MOSFETs under three different gate bias conditions (*i.e.* grounded, 0.5V above/below V_{th}, respectively). As seen, negative gate bias (0.5V below V_{th}) during x-ray irradiation gives rise to noticeably larger negative ΔV_{th} (~42 mV@ 1Mrad) than gate grounded or positively biased. Correspondingly, low-frequency (1/*f*) noise scan from subthreshold to the strong inversion region indicates that radiation under negative gate bias results in 2X higher spectral density of drain current than the case of gate grounded (refer to Fig.13). As S_{Id}/I_d^2 is proportional to the oxide trap density, the 1/*f* measurement result may very well mean that more oxide traps are generated during x-ray irradiation as the gate is negatively biased, thus more holes are getting trapped in the oxide, leading to greater threshold voltage shifts.

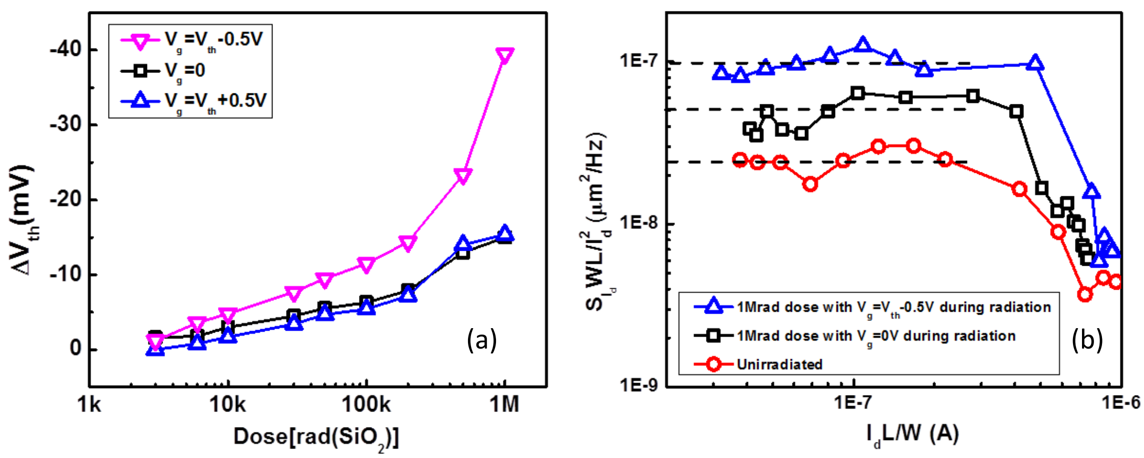


Fig. 13, (a) ΔV_{th} as functions of radiation dose for InGaAs NW GAA MOSFETs under various gate bias conditions during radiation; (b) Low-frequency *1/f* noise measurements on NW GAA MOSFETs under two different bias conditions during radiation. Red circles represent data taken on a non-irradiated device for comparison.

VI. Sentaurus TCAD similation

In order to understand better the NW thickness dependence of the TID effect, we used Sentaurus TCAD to simulate the inversion carrier distribution and electric field in the NW devices with NW thickness as the variable. Figs. 14(a) and (b) show the cross-sectional views of inversion electron density distribution in devices with 10 nm and 20 nm NW thickness, respectively. As seen in Fig.14(b), the inversion electrons are distributed more towards the surfaces than in the center for the 20nm NW, which is quite different from the case of 10nm NW (refer to Fig.14(a)). Such difference can be better illustrated in Fig. 15, where the cross-sectional views of the electric field for the two devices are shown. Similation of the electric fields in the gate oxides of the two devices is underway to find out how the electric field within the nanowire chanel would affect the electric field in the gate oxide that eventually causes varying degrees of hole trapping.

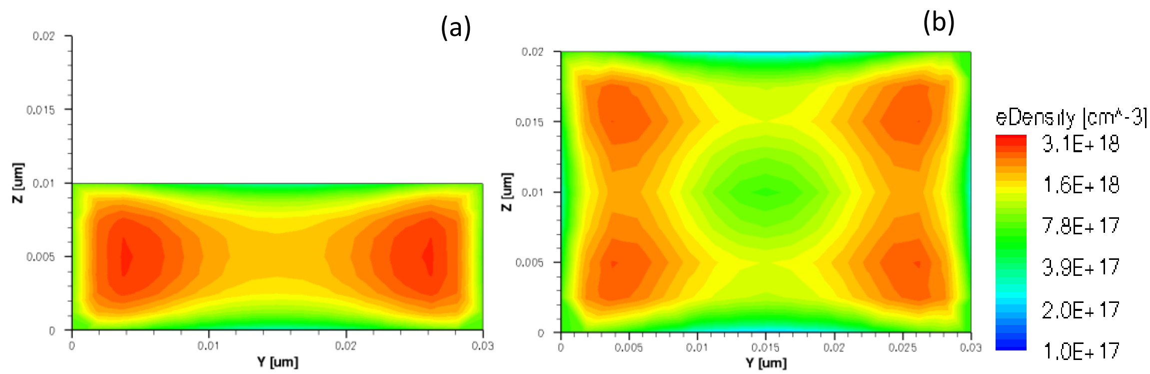


Fig.14, TCAD simulation of inversion carrier distibutions in InGaAs NW devices with (a) 10-nm channel (b) 20-nm channel at Vg=0V.

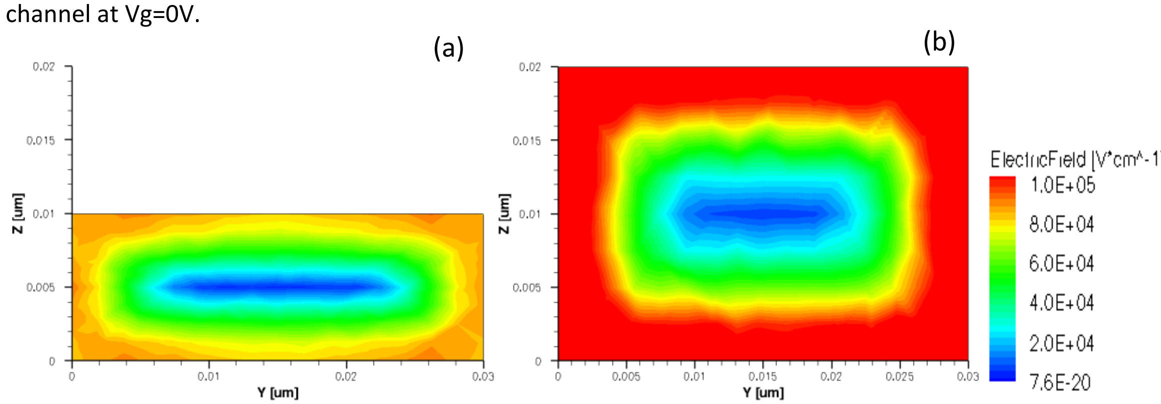


Fig. 15, Cross-section view of electric field within (a) 10 nm; (b) 20nm NW of the same devices at Vg=0V

VII. IETS study of X-ray induced traps in AlGaN/GaN HEMTs and their subsequent transformation in energy upon post-irradation room temperature storage

In our last annual report we noted that x-ray irradiation led to a prominent change in the IETS spectra of AlGaN/GaN HEMTs – the appearance of a huge and broad "down-up-down" trap feature approximately in the gate voltage range of -0.3V to -0.5 V. This trap feature is indicative of a high density of electron traps generated by X-ray irradiation in the AlGaN layer, and the energy levels of these traps are in the range (or a band) of 0.3-0.5eV above the GaN conduction band minimum. We also noted that the centroid of this trap energy band tends to shift upwards during the post-irradiation room temperature storage. Fig. 16 shows an example of such shift after 700 hours of storage for the sample that received an initial 1.5Mrad X-ray irradiation. More interestingly, repeated x-ray exposures (independent of the x-ray dose) on the same sample reset this trap feature back to its original energy position, and from there it started to shift upwards again in the subsequent room temperature storage. In the past year we carried out further investigation on the possible mechanism(s) behind such trap energy transformation.

To verify our hypothesis that the aforementioned broad "down-up-down" IETS feature is caused by electron trapping, we performed a "stress-relaxation test" on a devicethat had shown such a huge trap feature after 1.5Mrad of x-ray exposure. At t =0, the device was biased at Vg = -1V. We expected to see no trap feature in the gate voltage range of -0.3V to -0.5V. Then the stress was removed (gate floating) and a serial IETS spectrum was taken at incremental relaxation intervals. As predicted by the IETS theory, the -1V gate bias indeed made this trap feature disappear. This means that the traps generated by x-ray irradiation were all filled, allowing no more tunneling electrons to get trapped as the gate voltage

swept over such a broad trap energy range. It is interesting to watch the trap feature "growing up" once the stress was removed due to electron de-trapping, and eventually the trap feature was able to restore to its original shape.
As IETS is the 2nd derivative of a tunneling current–gate voltage curve, a trap feature in a shape of "down-up-down" or a "valley followed by a peak" should correspond to a ledge (caused by electron trapping) in the I-V curve. We then checked/compared two I-V curves, of which one was taken immediately after x-ray irradiation and the other after 1735 hours of post-radiation room temperature storage. As shown in Fig. 18, there is indeed a ledge in each I-V curve, and most interestingly, the I-V curve shifted in the direction of electron trapping after 1735 hours storage .

We then measured the time intervals required for the ΔV_{trap} to saturate at various storage temperatures. Fig. 19 shows that, although at higher storage temperatures ΔV_{trap} reaches its saturation level faster, the curve fitting results in a time constant on the order of hundreds of hours! We believe that when the gate is floating while the device is stored in the air, the electron traps in the microstructural defective region near the AlGaN/GaN interface start to exchange charges with the 2DEG at the AlGaN/GaN interface, resulting in the apparent energy shift of the IETS trap feature. The charging (or electron trapping) process takes place over a long time period, therefore may raise a serious concern over the device reliability.

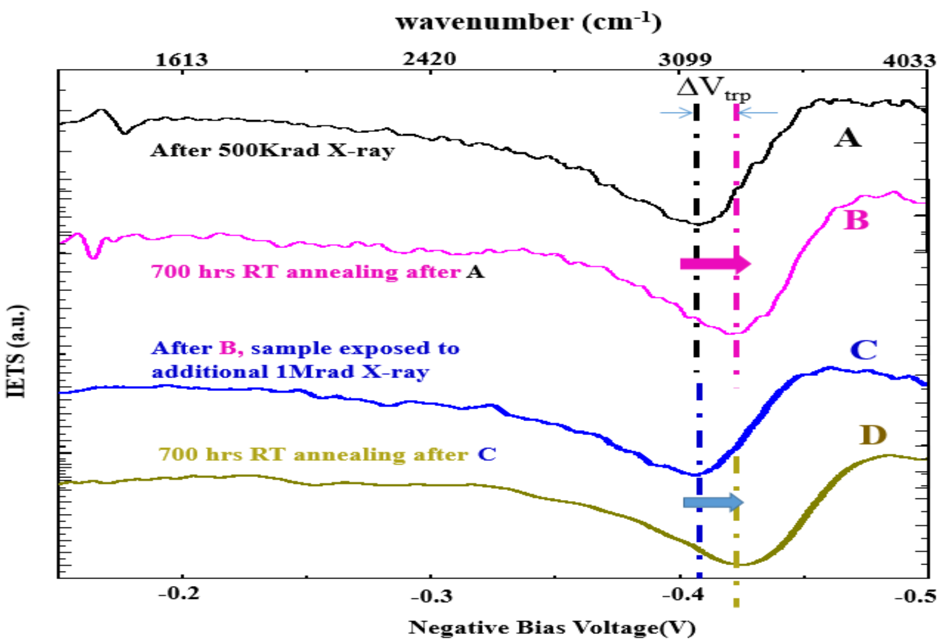


Fig. 16, Energy levels of the electron traps tend to shift upwards away from the GaN conduction band minimum. (a) IETS collected after 1.5Mrad X-ray irradiation on an AlGaN/GaN HEMT; (b) IETS of the same device stored at room temperature for 700 hours after X-ray exposure

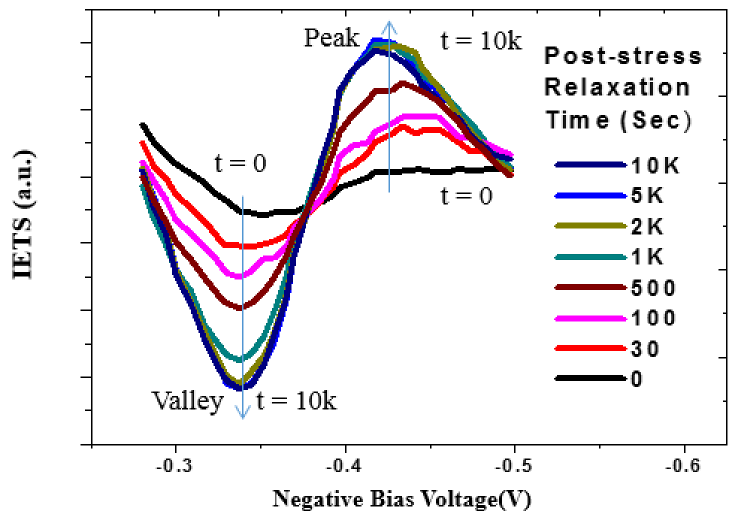


Fig. 17, IETS traces of the broad electron trap feature at incremental stress-relaxation intervals

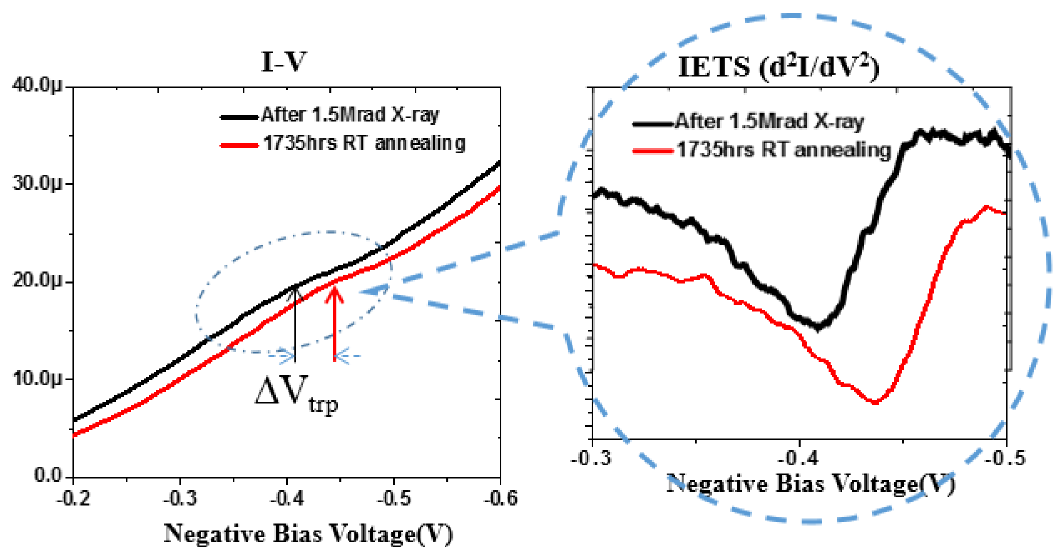


Fig. 18, Tunneling current I as functions of gate voltage taken immediately after 1.5Mrad x-ray exposure (black) and after 1735hours room temperature storage (red); The 2nd derivative of the I-V curves in the voltage range, where a ledge appears, is shown in the "blow-up" figure on the right.

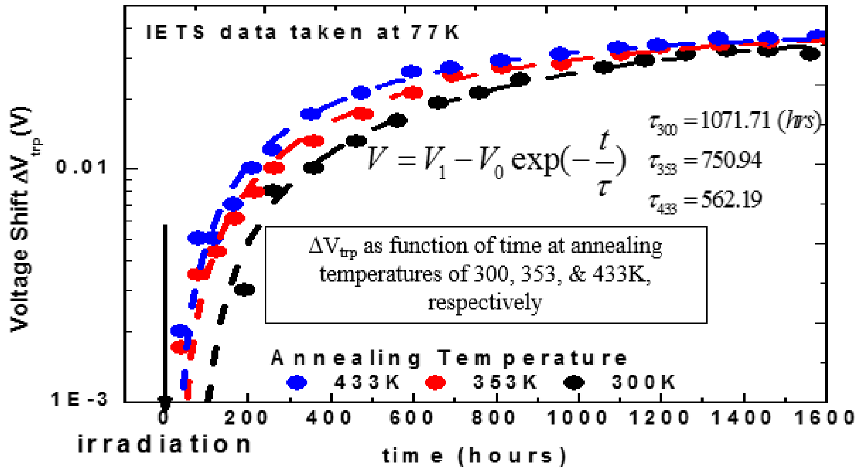


Fig. 19, ΔV_{trap} as functions of time at three storage temperatures.

What opportunities for training and professional development has the project provided?

Three Ph.D students and a post-doctoral fellow have been involved in this project under the supervision of Prof. Ma and a senior research scientist, Dr. Sharon Cui, in his laboratory. In addition to taking required courses, students also attended extensive hands-on training courses for semiconductor device processing conducted by Yale's Cleanroom staff. They also received trainings on experimental design methodology and on improving writing/presentation skills. This group holds weekly group meetings with the other members of Prof. Ma's research group to discuss research progress, research plans, and exchange ideas. In addition, these students are provided the opportunity to work one-on-one with the senior research scientist on a daily basis. All these students have participated in conferences and workshops in related fields, as well as research project reviews. Two of them have also visited our collaborator's laboratory (Vanderbilt's X-ray irradiation facility), where they did some experiments jointly with our collaborators.

How have the results been disseminated to communities of interest?

They have been published in refereed journals and presented at professional conferences, as shown below

Publication list:

- Journal papers:

1. Z. G. Liu and T. P. Ma," **Determination of Energy and Spatial distributions of Traps in Ultra-thin Dielectrics by Use of Inelastic Electron Tunneling Spectroscopy**" *Applied Physics Letters* 97 (17), 172102 (2010).
2. Zuoguang Liu, Sharon Cui, Lior Kornblum, Ming-Feng Chang, and Tso-Ping Ma, "**Inelastic Electron Tunneling Spectroscopy Study of Ultra-Thin Al_2O_3-TiO_2 Dielectric Stack on Si**", *Appl. Phys. Lett*. 97, 202905 (2010)
3. T.P. Ma, "**Inelastic Electron Tunneling Spectroscopy (IETS) Study of Ultra-Thin Gate Dielectrics for Advanced CMOS Technology**" *ECS Trans*. 35 (4), 545 (2011)
4. X. Sun, O.J. Saadat, K.S. Chang-Liao, T. Palacios, S. Cui, and T.P. Ma, **"Study of gate oxide traps in HfO2/AlGaN/GaN metal-oxide-semiconductor high-electron-mobility transistors by use of ac transconductance method",** *Applied Physics Letters***,** vol.102(10), pp.103504 - 103504-4 (2013)
5. X. Sun, F. Xue, J. Chen, E. X. Zhang, S. Cui, J. Lee, D. M. Fleetwood, and T. P. Ma**. "Total ionizing dose radiation effects in Al_2O_3-gated ultra-thin body $In_{0.7}Ga_{0.3}As$ MOSFETs**", *IEEE Trans. on Nuclear Sci.*, TNS-60, pp. 402-407, (2013)
6. Jie Yang, Sharon Cui, T.P. Ma, Ting-Hsiang Hung, Digbijoy Nath,, Sriram Krishnamoorthy, and Siddharth Rajan, "**A Study of Electrically Active Traps in AlGaN/GaN HEMT**", *Appl. Phys. Lett***.** 103, 173520 (2013)
7. **X**. Sun and T.P. Ma, **"Electrical Characterization of Gate Traps in FETs with Ge and III-V Channels", Invited Paper,** *IEEE Transactions on Device and Materials Reliability, TDMR Vol-13(4),* pp.463-479 (2013).
8. Jie Yang, Sharon Cui, T.P. Ma Ting-Hsiang Hung, Digbijoy Nath, Sriram Krishnamoorthy, and Siddharth Rajan, **"Electron Tunneling Spectroscopy Study of Electrically Active Traps in** AlGaN/GaN HEMT**",** *Appl. Phys. Lett.* 103, 223507 (2013)
9. X. Sun, O. I. Saadat, J. Chen, E. X. Zhang, S. Cui, T. Palacios, D. M. Fleetwood, and T. P. Ma, **"Total-Ionizing-Dose Radiation Effects in AlGaN/GaN HEMTs and MOS-HEMTs",** IEEE Transactions on Nuclear Science, Vol. NS-60 (6), pp. 4074-4079 (2013).
10. X. Sun, Y. Zhang, K. S. Chang-Liao T. Palacios, and T. P. Ma, "**Impacts of Fluorine-treatment on E-mode AlGaN/GaN MOS-HEMTs** ", IEDM Technical Digest, December (2014).
11. Xiao Sun and T.P. Ma, "**Electrical Characterization of Nanoscale Transistors —with an Emphasis on Traps Associated with the MOS Gate Stacks**" book chapter for "Characterization and Metrology for Nanoelectronics and Nanostructures", edited by Zhiyong Ma and Dave Seller, to be published in June (2015).

- Conference Presentations:

1. Zuoguang Liu, Sharon Cui, and T.P. Ma, "**Study of Trap Distribution in Ultra-Thin Dielectrics by Inelastic Electron Tunneling Spectroscopy**", *2010 IEEE-SISC*, San Diego, California, Dec. 2-4 (2010).
2. Zuoguang Liu, Sharon Cui, and T.P. Ma," **Inelastic Electron Tunnelling Spectroscopy (IETS) Study of High-k Gate Dielectrics on GaAs and InGaAs"**, 219th ECS Meeting , Montreal, QC, Canada, May 1 - May 6, (2011).
3. Zuoguang Liu, Sharon Cui, and T.P. Ma "**Inelastic Electron Tunneling Spectroscopy (IETS) Study of Ionizing Radiation Effects on High-k Gate Dielectrics for CMOS Transistors**", GomacTech, Orlando, FL, March 21-24 (2011)
4. X.Sun, S. Cui, F. Xue, J. Chen, E. X. Zhang, J. Lee, D. M. Fleetwood and T.P. Ma, " **Ionizing Radiation Effects in Al_2O_3-Gated Ultra-thin Body $In_{0.7}Ga_{0.3}As$ MOSFETs**" , 2012 IEEE/SISC, Dec (2012)

5. Jie Yang, Sharon Cui, Xiao Sun, Zuoguang Liu, and T.P. Ma *et al*. "**Probing Electrically Active Traps in AlGaN/GaN HEMT by Inelastic Electron Tunneling Spectroscopy**", 2012 IEEE/SISC, Dec (2012)
6. X. Sun, O. I. Saadat, E. X. Zhang, S. Cui, T. Palacios, D. M. Fleetwood, and T. P. Ma, "**Ionizing Radiation Induced Threshold Voltage Shifts in GaN MOS-HEMTs on Si Substrates**", presented at IEEE Nuclear and Space Radiation Effects Conference (2013)
7. Jie Yang, Sharon Cui, Ting-Hsiang Hung, Digbijoy Nath, Sriram Krishnamoorthy Siddharth Rajan and T.P. Ma, "**Study of Traps in AlGaN/GaN HEMT and Their Role in Electron Transport Process**", presented at IEEE Device Research Conference, Notre Dame, June (2013)
8. S. Ren, X. Sun, M. Si, E. X. Zhang, J. Chen, D. M. Fleetwood, P. D. Ye, S. Cui, and T. P. Ma," **Total Ionizing Dose (TID) Effects on Ultra-thin InGaAs Nanowire Gate-All-Around MOSFETs with ALD Al_2O_3 Gate Dielectrics**", *2013 IEEE-SISC*, Arlington, Va, Dec.5-7, (2013).
9. Jie Yang, Xiao Sun, Shufeng Ren, Sharon Cui, and T.P. Ma,"**X-ray Induced Electron Trapping in AlGaN/GaN HEMTs**", *2013 IEEE-SISC*, Arlington, Va, Dec.5-7, (2013)
10. Jie Yang, Xiao Sun, Shufeng Ren, Sharon Cui, and T.P. Ma, "**Study of Electron Trapping in AlGaN/GaN HEMTs under X-ray Irradiation**", 23rd Annual CMOC Symposium, UConn, Storrs, CT, April 9th (2014).
11. S. Ren, X. Sun, M. Si, E. X. Zhang, J. Chen, D. M. Fleetwood, P. D. Ye, S. Cui, and T. P. Ma, "**Total Ionizing Dose (TID) Effects on Ultra-thin InGaAs Nanowire Gate-All-Around MOSFETs with ALD Al2O3 Gate Dielectrics**", 23rd Annual CMOC Symposium, UConn, Storrs, CT, April 9th (2014)
12. S. Ren, M. Si, K. Ni, S. Chang, X. Sun, E. X. Zhang, D. M. Fleetwood, P. D. Ye, S. Cui, T. P. Ma, "**A Study of Factors Affecting Radiation Hardness of InGaAs Nanowire Gate-All-Around MOSFETs**", *2014IEEE-SISC*, San Diego, CA, Dec.10-13, (2014).
13. X. Sun, Y. Zhang, K. S. Chang-Liao T. Palacios, and T. P. Ma, "**Impacts of Fluorine-treatment on E-mode AlGaN/GaN MOS-HEMTs** ", International Electron Device Meeting (IEDM), San Francisco, Ca, December 14-17 (2014).
14. S. Ren, M. Si, K. Ni, S. Chang, X. Sun, E. X. Zhang, D. M. Fleetwood, P. D. Ye, S. Cui, and T. P. Ma, "**A Study of Radiation Hardness of InGaAs Nanowire Gate-All-Around MOSFETs**", 40th Annual GOMACTech Conference, St. Louis, MO, March 23-26, 2015
15. S. Ren, M. Si, K. Ni, S. Chang, X. Sun, E. X. Zhang, D. M. Fleetwood, P. D. Ye, S. Cui, and T. P. Ma, **"A Study of Radiation Hardness of InGaAs Nanowire Gate-All-Around MOSFETs",** *24th Annual CMOC Symposium, Storrs, Connecticut, April 1st, 2015:*

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