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Proton radiation hardness of single-nanowire transistors using robust organic gate nanodielectrics

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In this contribution, the radiation tolerance of single ZnO nanowire field-effect transistors (NW-FETs) fabricated with a self-assembled superlattice (SAS) gate insulator is investigated and compared with that of ZnO NW-FETs fabricated with a 60 nm SiO₂ gate insulator. A total-radiation dose study was performed using 10 MeV protons at doses of 5.71 and 285 krad(Si). The threshold voltage (V_{th}) of the SAS-based ZnO NW-FETs is not shifted significantly following irradiation at these doses. In contrast, V_{th} parameters of the SiO₂-based ZnO NW-FETs display average shifts of ~ -4.0 and ~ -10.9 V for 5.71 and 285 krad(Si) H⁺ irradiation, respectively. In addition, little change is observed in the subthreshold characteristics (off current, subthreshold slope) of the SAS-based ZnO NW-FETs following H⁺ irradiation. These results strongly argue that the bulk oxide trap density and interface trap density formed within the SAS and/or at the SAS-ZnO NW interface during H⁺ irradiation are significantly lower than those for the corresponding SiO₂ gate dielectrics. The radiation-robust SAS-based ZnO NW-FETs are thus promising candidates for future space-based applications in electronics and flexible displays. © 2006 American Institute of Physics. [DOI: 10.1063/1.2336744]

Since the first discovery of radiation-induced damage in metal-oxide-semiconductor field-effect transistors (MOSFETs) in the early 1960s, many studies have focused on hardening MOSFETs to various radiation effects, particularly for military and space electronics applications.¹ The radiation sensitivity of MOSFETs results mainly from radiation-induced trapped charges built up in the gate oxide and at oxide-semiconductor interfaces, which modify the MOSFET behavior and, accordingly, degrade the performance and reliability of integrated circuits. One of the most pronounced radiation effects, a negative shift in threshold voltage (V_{th}) due to positive oxide trap charges, diminished as gate oxide (SiO₂) thicknesses fell below 10 nm.² However, radiation-induced leakage currents remain problematic because the gate leakage current is a major limitation of MOSFETs. Although high- κ gate dielectric materials such as Al₂O₃ are being considered, these materials may not guarantee immunity from V_{th} shifts.² Therefore, there is a significant need to develop radiation-robust devices and gate insulators.

Semiconductor nanowires are being investigated as channel regions for devices in general purpose microelectronics as well as in flexible electronic/optoelectronic applications.³⁻⁵ Likewise, self-assembled superlattice (SAS) nanodielectrics show promise as high- κ gate dielectric materials for both organic and inorganic FETs.⁶⁻⁸ We have re-

cently demonstrated SAS-based thin-film devices, including ZnO nanowire FETS (NW-FETs), which show potential as building blocks for high-performance transparent and flexible electronics.⁸ Despite the great interest in both classes of materials, little is known about their stability and robustness with regard to total integrated radiation doses. In addition to bulk material issues, nanowires have a relatively large surface:volume ratio, and their electrical properties can be very dependent on interface states. Studies of their stability in device structures can help establish their potential as materials for electronic and optoelectronic devices.

In this letter, we report a study of the total-dose radiation effects on ZnO NW-FETs fabricated with SAS gate dielectrics and a comparison to comparable devices using SiO₂ gate dielectrics. ZnO is a wide band gap (~ 3.4 eV) semiconductor and is of interest for a variety of electronic and optoelectronic applications.^{9,10} Single ZnO NW-FET devices using SAS or SiO₂ as gate insulators were fabricated with a conventional bottom-gate structure (Fig. 1). The high-capacitance, low-leakage "type III" nanodielectric is composed of four three-dimensional cross-linked σ - π siloxane layers, sequentially deposited via self-limiting deposition of organosilane precursors: (i) α , ω -difunctionalized hydrocarbon chains, (ii) highly polarizable push-pull π layers, and (iii) capping layers to planarize, cross-link, and seal pinholes.¹¹ An ~ 15 nm dielectric stack of three sequentially deposited type III nanodielectric layers was deposited on clean n⁺-Si substrates. The thickness of the SAS dielectric is ~ 15 nm, corresponding to a specific capacitance of $C_{ox} = 180$ nF/cm². For the SiO₂ device, a thicker dielectric,

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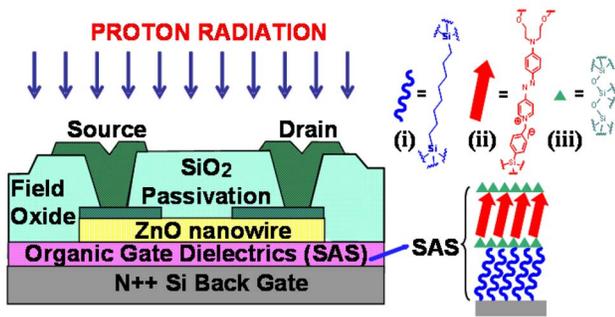


FIG. 1. (Color online) Cross-sectional view of SAS-based ZnO NW-FET device structure, Type III SAS.

60 nm ($C_{ox}=48$ nF/cm²), is used in order to provide low gate leakage. The crystalline ZnO nanowires (NanoLab Inc.) were dispersed in very large scale integrated grade isopropanol, and the dispersion was transferred onto SAS-coated Si wafers. Aluminum source-drain electrodes with a thickness of 140 nm were subsequently deposited by electron beam evaporation at $\sim 5 \times 10^{-7}$ Torr (deposition rate=0.3 Å/s). Details of the SAS properties⁶⁻⁸ and ZnO NW-FET fabrication⁸ have been described previously. Subsequently, all the ZnO NW-FET devices were subjected to an ozone treatment for 1 min in order to improve the subthreshold slopes and on currents, presumably due to a reduction in surface state density. Finally, all the devices were passivated with SiO₂ (~ 300 nm) to prevent contamination from air/moisture.

SAS-based and SiO₂-based ZnO NW-FETs with the same nominal wire diameter ($W \sim 120$ nm) and channel length ($L \sim 2$ μm) were irradiated with 10 MeV protons to fluences of 1×10^{10} and 5×10^{11} p/cm² with average fluxes (p/cm²/s) of $\sim 2.11 \times 10^7$ and 1.67×10^7 , respectively. The radiation fluences correspond to total integrated doses of 5.71 and 285 krad(Si), respectively. The irradiation took place at room temperature in a vacuum of about 3×10^{-5} Torr. The proton beam had a square 5×5 cm² cross section and a uniformity of about 90% or better. The two doses correspond to the cumulative doses expected over approximately 2 weeks and 2 years in low earth orbit (LEO), respectively, and the higher dose corresponds to approximately one-quarter of the total dose (1 Mrad) that would be required for an unmanned Mars mission. Protons found in orbits designated as LEO (usually considered <1000 km) have a widely varying energy spectra from tens of keV to the GeV range.¹¹ The proton energy for the present experiments is chosen due to availability, to be representative of a significant component of the proton spectra in LEO orbits and, of the proton energies available, to produce maximum damage. The current-voltage characteristics of the devices were measured before and after H⁺ irradiation using a probe station with a HP 4156A semiconductor parameter analyzer.

Measured drain current versus drain-source voltage ($I_{ds}-V_{gs}$) characteristics are shown for representative SAS and SiO₂-based NW-FETs in Fig. 2. Data are shown before and after irradiation at the respective doses. Negligible changes are observed in the current-voltage characteristics for unirradiated control devices, indicating that the passivation layers render the devices stable during exposure to ambient. For the SiO₂-based ZnO NW-FETs [Fig. 2(a)], the threshold voltages shift substantially in the negative direction

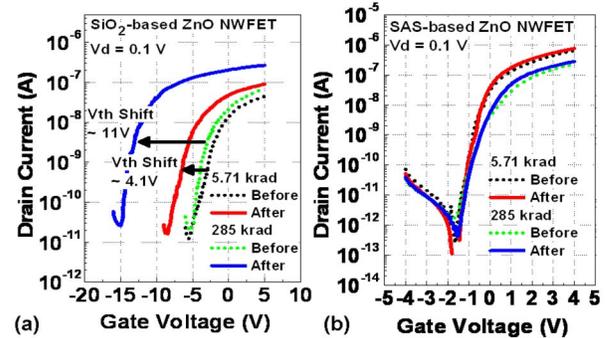


FIG. 2. (Color online) (a) $I_{ds}-V_{gs}$ for a NW-FET with a SiO₂ gate dielectric. (b) $I_{ds}-V_{gs}$ for a NW-FET with a SAS gate dielectric.

upon proton irradiation. Figure 3(a) shows the measured shift in V_{th} following irradiation ($-V_{th}$) for six SiO₂-based devices for each of the radiation doses. The average V_{th} shifts are -4.1 V for 5.71 krad(Si) and -10.9 V for 285 krad(Si). These shifts can be generally associated with the generation of positive trap states in the SiO₂ dielectric or at the ZnO NW-SiO₂ interface. Since the subthreshold slope and off current remain essentially unchanged after irradiation, the trap states do not appear to change with voltage, implying that either bulk SiO₂ states or interface states deep in the band gap dominate. Furthermore, no mobility degradation is observed, indicating that interfacial trap densities are not significantly increased. It is known that radiation-induced interface traps are generated by breaking Si-H bonds at the Si-SiO₂ interface.¹ Because as-grown SiO₂ was used here without hydrogen passivation, changes in interfacial trap density upon irradiation are assumed to be absent. The behavior of the SiO₂-based ZnO NW-FETs upon proton irradiation is consistent with previous studies of FETs using SiO₂ dielectrics¹²⁻¹⁴ and suggests an increase of the positive fixed charges in the bulk oxide.

In contrast, the SAS-based ZnO NW-FETs exhibit a high degree of stability upon H⁺ irradiation. Figure 3(b) shows the measured shifts in V_{th} for SAS-based ZnO NW-FETs, again showing six devices at each dose. Note that values are rounded to the nearest 0.1 V, corresponding to an estimate of the precision in extracting V_{th} . The average V_{th} shifts observed in SAS-based ZnO NW-FETs [Fig. 2(b)] are 0.02 V for 5.71 krad(Si) and 0.07 V for 2.85 krad(Si). Since these values are within the accuracy of our measurement system, it is concluded that there are negligible V_{th} shifts in

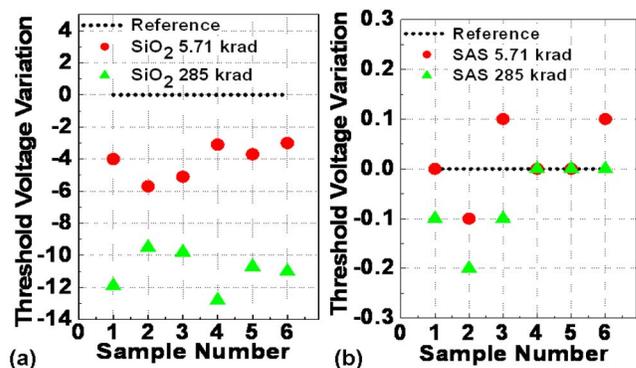


FIG. 3. (Color online) (a) Threshold voltage variation of SiO₂-based ZnO NW-FETs (b) Threshold voltage variation of SAS-based ZnO NW-FETs.

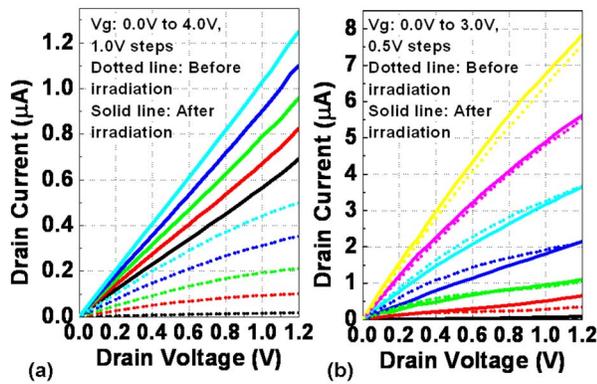


FIG. 4. (Color online) (a) I_{ds} - V_{ds} characteristics for a SiO_2 -based ZnO NW-FET before (dotted curves) and after (solid curves) 5.71 krad(Si) proton irradiation. (b) I_{ds} - V_{ds} characteristics for a SAS-based ZnO NW-FET before (dotted curves) and after (solid curves) 5.71 krad(Si) proton irradiation.

the SAS-based devices upon proton irradiation. As shown in Fig. 2(b), the subthreshold slope and off current levels remain essentially unchanged. A modest improvement in current is observed, which may correspond to radiation-induced annealing effects. This result illustrates the robustness of the SAS-based ZnO NW-FETs upon proton irradiation.

The drain current (I_{ds}) versus drain-source voltage (V_{ds}) characteristics of a representative SAS-based ZnO NW-FET ($L \sim 2.2 \mu\text{m}$) before and after 5.71 krad(Si) proton irradiation are shown in Fig. 4(b). The device displays typical I_{ds} - V_{ds} characteristics of a n -type FET. This single-nanowire device exhibits an “on” current of $\sim 8.0 \mu\text{A}$ at $V_{ds} = 1.2 \text{ V}$ and $V_{gs} = 3.0 \text{ V}$. Negligible change is observed following irradiation, with no evidence of contact degradation or leakage. This result indicates that the SAS is robust under proton irradiation, and that the ZnO nanowires themselves are also unaffected by proton irradiation. Before irradiation, a SiO_2 -based ZnO NW-FET device [$L \sim 2.2 \mu\text{m}$, Fig. 4(a)] shows a significantly lower current than the SAS-based NW-FET, with a transconductance approximately 20 times smaller. This is due to the lower specific capacitance as well as to a lower effective mobility.⁸ After 5.71 krad(Si) proton irradiation [Fig. 4(a)], the I_{ds} - V_{ds} curves deviate significantly from the expected response of a long-channel transistor, exhibiting a significant slope even at V_{ds} values expected to be in the saturation region. Note that the irradiated device has a threshold voltage of approximately -4 V , so the actual ($V_{gs} - V_{th}$) is significantly larger than that for the SAS-based device at the same gate bias. Even at the larger effective gate biases, the device has a significantly lower current ($\sim 1.1 \mu\text{A}$ per ZnO NW at $V_{ds} = 1.2 \text{ V}$ and $V_{gs} = 3.0 \text{ V}$) than the SAS-based device.

A full explanation for the radiation robustness of the SAS nanodielectric requires detailed microstructural and electronic structure information not currently available. However, a plausible mechanism is suggested by what is known about radiation-induced trap generation processes in SiO_2 . The mechanism for trapped charge buildup associated with radiation exposure in conventional MOSFETs is well established.^{1,2,12-14} When radiation passes through the gate oxide, electron-hole pairs are generated. Because the electrons in SiO_2 are much more mobile than the holes, the elec-

trons are immediately swept out of the oxide. However, the relatively immobile holes remain in the oxide and become positive bulk oxide traps (Q_{OT}). In addition, some percentage of the holes reach the Si-SiO₂ interface via hopping transport and form positive deep-level trap states (Q_F). The observation of significant changes in SiO_2 -based device performance can readily be explained in terms of these trap states within the SiO_2 and near the SiO_2 -nanowire interface. The lack of significant changes in device performance for the NW-FETs on the SAS dielectric indicates that the number of positive trap states generated by irradiation is significantly lower than in SiO_2 . Whether these effects are due to differences in the generation rate of electron-hole pairs in the SAS or to a lower probability that an electron-hole pair in the SAS forms a trap state will be the subject of future experiments.

We have demonstrated that single ZnO NW-FETs using a SAS gate dielectric exhibit impressive tolerance to proton irradiation, with the average threshold voltage shifts of less than 0.02 V at 5.71 krad(Si) and 0.07 V at 2.85 krad(Si). In contrast, ZnO NW-FETs fabricated using conventional SiO_2 gate dielectrics exhibit significant deterioration in both subthreshold properties and above-threshold current-voltage relationships. These results indicate that SAS-based NW-FETs exhibit much greater radiation hardness than comparable devices on SiO_2 , presumably due to the generation of significantly less bulk oxide traps and interface traps in the SAS on proton irradiation. These results therefore show that robust ZnO-SAS NW-FETs are excellent candidates for future space electronics applications.

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¹T. R. Oldham and F. B. McLean, IEEE Trans. Nucl. Sci. **50**, 483 (2003).

²H. L. Hughes and J. M. Benedetto, IEEE Trans. Nucl. Sci. **50**, 500 (2003).

³P. K. H. Ho, D. S. Thomas, and H. Siringhaus, Science **299**, 1881 (2003).

⁴H. E. A. Huitema, G. H. Gelinck, J. B. P. H. van der Putten, K. E. Kuijk, C. M. Hart, E. Cantatore, P. T. Herwig, A. J. J. M. van Breemen, and D. M. de Leeuw, Nature (London) **414**, 599 (2001).

⁵D. Whang, S. Jin, and C. M. Lieber, Jpn. J. Appl. Phys., Part 1 **43**, 4465 (2004).

⁶M.-H. Yoon, A. Facchetti, and T. J. Marks, Proc. Natl. Acad. Sci. U.S.A. **102**, 4678 (2005).

⁷S.-H. Hur, M.-H. Yoon, A. Gaur, A. Facchetti, T. J. Marks, and J. A. Rogers, J. Am. Chem. Soc. **127**, 13808 (2005).

⁸S. Ju, K. Lee, D. B. Janes, M.-H. Yoon, A. Facchetti, and T. J. Marks, Nano Lett. **5**, 2281 (2005).

⁹J. A. Rodriguez, T. Jirsak, S. Sambasivan, D. Fischer, and A. Maiti, J. Chem. Phys. **112**, 9929 (2000).

¹⁰K. Hara, T. Horiguchi, T. Kinoshita, K. Sayama, H. Sugihara, and H. Arakawa, Sol. Energy Mater. Sol. Cells **64**, 115 (2000).

¹¹E. G. Stassinopoulos and J. P. Raymond, Proc. IEEE **76**, 1423 (1988).

¹²E. Simoen, A. Mercha, A. Morata, K. Hayama, G. Richardson, J. M. Rafi, E. Augendre, C. Claeys, A. Mohammadzadeh, H. Ohyama, and A. Romano-Rodriguez, IEEE Trans. Nucl. Sci. **50**, 2426 (2003).

¹³P. Paillet, J. R. Schwank, M. R. Shaneyfelt, V. Ferlet-Cavros, R. L. Jones, O. Flament, and E. W. Blackmore, IEEE Trans. Nucl. Sci. **49**, 2656 (2002).

¹⁴D. M. Feetwood, T. L. Meisenheimer, and J. H. Schfield, IEEE Trans. Electron Devices **50**, 483 (2003).