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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.

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-\(\kappa\) 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-\(\kappa\) gate dielectric materials for both organic and inorganic FETs.6−8 We have recently 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.6 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 \(\sigma\)-\(\pi\) siloxane layers, sequentially deposited via self-limiting deposition of organosilane precursors: (i) \(\sigma\)-\(\omega\)-difunctionalized hydrocarbon chains, (ii) highly polarizable push-pull \(\pi\) 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,
60 nm ($C_{ox}=48 \text{nF/cm}^2$), 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 $\approx 5 \times 10^{-7}$ Torr (deposition rate=0.3 Å/s). Details of the SAS properties and ZnO NW-FET fabrication 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 SiO$_2$ ($\approx 300$ nm) to prevent contamination from air/moisture.

SAS-based and SiO$_2$-based ZnO NW-FETs with the same nominal wire diameter ($W \approx 120$ nm) and channel length ($L \approx 2$ μm) were irradiated with 10 MeV protons to fluences of $1 \times 10^{10}$ and $5 \times 10^{11}$ p/cm$^2$ with average fluxes (p/cm$^2$/s) of $\approx 2.11 \times 10^5$ and $1.67 \times 10^7$, 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 $3 \times 10^{-5}$ Torr. The proton beam had a square 5 × 5 cm$^2$ 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 SiO$_2$-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 SiO$_2$-based ZnO NW-FETs [Fig. 2(a)], the threshold voltages shift substantially in the negative direction upon proton irradiation. Figure 3(a) shows the measured shift in $V_{th}$ following irradiation ($-V_{th}$) for six SiO$_2$-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 SiO$_2$ dielectric or at the ZnO NW-SiO$_2$ 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 SiO$_2$ 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–SiO$_2$ interface.$^1$ Because as-grown SiO$_2$ was used here without hydrogen passivation, changes in interfacial trap density upon irradiation are assumed to be absent. The behavior of the SiO$_2$-based ZnO NW-FETs upon proton irradiation is consistent with previous studies of FETs using SiO$_2$ dielectrics$^{12–14}$ 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-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 285 krad(Si). Since these values are within the accuracy of our measurement system, it is concluded that there are negligible $V_{th}$ shifts in...
SiO₂. The mechanism for trapped charge buildup associated with proton irradiation is not fully known about radiation-induced trap generation processes in SiO₂. However, a plausible mechanism is suggested by what is inferred from electronic structure information not currently available.

The current drain density ($I_D$) versus drain-source voltage ($V_{DS}$) characteristics of a representative SAS-based SiO₂ NW-FET ($L \sim 2.2 \, \mu m$) before and after 5.71 kradi(Si) proton irradiation are shown in Fig. 4b. The device displays typical $I_D$-$V_{DS}$ characteristics of a n-type FET. This single-nanowire device exhibits an “on” current of $\sim 8.0 \, \mu A$ at $V_{DS}=1.2 \, V$ and $V_{GS}=3.0 \, V$. 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 SiO₂ nanowires themselves are also unaffected by proton irradiation. Before irradiation, a SiO₂-based SiO₂ NW-FET device ($L \sim 2.2 \, \mu m$) 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. After 5.71 kradi(Si) proton irradiation [Fig. 4(a)], the $I_D$-$V_{DS}$ 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 bias, the device has a significantly lower on current ($\sim 1.1 \, \mu A$ per ZnO NW at $V_{DS}=1.2 \, V$ and $V_{GS}=3.0 \, V$) 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 SiO₂. The mechanism for trapped charge buildup associated with radiation exposure in conventional MOSFETS is well established.²,¹²,¹³ When radiation passes through the gate oxide, electron-hole pairs are generated. Because the electrons in SiO₂ are much more mobile than the holes, the electrons 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 ($Q_{D}$).

The observation of significant changes in SiO₂-based device performance can readily be explained in terms of these trap states within the SiO₂ and near the SiO₂-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 SiO₂. 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 kradi(Si) and 0.07 V at 2.85 kradi(Si). In contrast, ZnO NW-FETs fabricated using conventional SiO₂ 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 SiO₂, 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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