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Fundamental Mechanisms and Control of Dielectric Breakdown in Electronic Materials

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14. ABSTRACT The physical mechanisms driving dielectric breakdown in electronic materials have assumed greater importance than ever with the emergence of semiconductors and dielectrics that can operate at extremely high voltages. While dielectric breakdown is pervasive in nature, it is critically important for the performance, reliability, and life of electronic devices operating under high applied electric bias. This work focused on (1) the fundamental mechanisms underlying dielectric breakdown in electronic materials and (2) methods for controlling these mechanisms and increasing dielectric strength in microelectronic heterostructures outlooked for high-speed, high-power devices under extremely high voltages. Both initiatives involved the measurement and control of native point defects using a combination of electron beam, optical, surface science, buried interface and plasma processing techniques. Depth-resolved cathodo-luminescence spectroscopy (DRCLS) combined with hyperspectral imaging (HSI) enabled us to determine the nature, electronic properties, densities, and spatial location of these defects on a nanometer scale and in three dimensions. We used DRCLS to characterize the optical and electronic properties, densities, and spatial movements of native point defects in the representative metal oxides ZnO, SrTiO ₃ , and Ga ₂ O ₃ single crystals, nanostructures, and device structures subject to high/extreme electric fields.			
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This final report of AFOSR grant FA9550-18-1-0066 entitled “Fundamental Mechanisms and Control of Dielectric Breakdown in Electronic Materials” describes our optical and electronic measurements of native point defects in three dimensions, the effects of plasma treatments, neutron irradiation, thermal annealing, atomic in-diffusion, high electric field biasing, and their relation to dielectric breakdown. Defects are central to dielectric breakdown since electrically active native point defects and impurities can change effective free carrier concentrations, open new conductive pathways, enable hopping-assisted tunneling, and increase local field gradients above critical breakdown fields. Enabling these measurements is a unique combination of optical, electronic, and surface science techniques.

We used depth-resolved cathodoluminescence spectroscopy (DRCLS) and surface photovoltage spectroscopy (SPS) to measure the effects of near-surface plasma processing and neutron irradiation on native point defects in β -Ga₂O₃. The near-surface sensitivity and depth resolution of these optical techniques enabled us to identify spectral changes associated with removing or creating these defects, leading to identification of one oxygen vacancy-related and two gallium vacancy-related energy levels in the β -Ga₂O₃ bandgap. The combined near-surface detection and processing of Ga₂O₃ suggests an avenue for identifying the physical nature and reducing the density of native point defects in this and other semiconductors.

We used depth-resolved cathodoluminescence spectroscopy, absorption spectroscopy, and temperature-dependent Hall effect (TDH) measurements to study the effects of fluence dependent neutron irradiations on deep level defects and the associated changes of electrical properties of β -Ga₂O₃ grown by low pressure chemical vapor deposition and pulsed laser deposition. DRCLS enabled us to monitor systematic increases of three deep level defects after neutron irradiation which correlated with TDH measurements of significant free carrier removal and mobility decrease. The correlations between defect profiles and electrical property changes vs. irradiation dose link these dominant electrically active native point defects in Ga₂O₃ with their contributions to free carrier mobility, carrier density, and donor/acceptor depth profiles, further revealing their donor/acceptor electrical behavior and physical nature, consistent with the formation of compensating defects. After irradiation, temperature-dependent forming gas (FG) anneals were performed to reverse the radiation-induced damage and carrier removal. The evolution of defect concentrations with increasing neutron dose and their depth-resolved distributions with FG anneal temperature reveal an interplay between specific defects to control electronic properties.

Laterally and depth-resolved cathodoluminescence spectroscopy (DRCLS) provided direct, nanoscale measurements of oxygen vacancy and oxygen vacancy complex distributions in undoped and Fe-doped SrTiO₃ with high temperature electric field stress associated with dielectric resistance degradation. DRCLS provided direct and spatially resolved observation of oxygen vacancy migration driven by external electric fields from the anode to the cathode in undoped SrTiO₃ between laterally separated electrodes, resulting in increased current leakage and lower thermal breakdown strength. DRCLS measurements through planar Pt electrodes after

high temperature electric field cycling reveal pronounced oxygen vacancy depletion within the surface space region of the Pt/ SrTiO₃ Schottky barrier as predicted theoretically. These results provide a direct insight into the transient states impacting the conduction during the electromigration of the oxygen vacancies. The deconvolution of different peaks and their intensity variations relative to the direct bandgap provide methods to gauge the relative defect energetics of these gap states. These data are discussed in relation to providing a tool to further understand conduction in mixed ionic conductors.

Plasma etching of p-type GaN creates n-type nitrogen vacancy (V_N) defects at the etched surface, which can be detrimental to device performance. In mesa isolated diodes, etch damage on the sidewalls degrades the ideality factor and leakage current. A treatment was developed to recover both the ideality factor and leakage current, which uses UV/O₃ treatment to oxidize the damaged layers followed by HF etching to remove them. The temperature dependent I–V measurement shows that the reverse leakage transport mechanism is dominated by Poole–Frenkel emission at room temperature through the etch-induced V_N defect. Depth resolved cathodoluminescence confirms that the damage is limited to first several nanometers and is consistent with the V_N defect.

The gallium vacancy is one of the dominant native point defects in β - Ga₂O₃, one that, together with its complexes, can have a major effect on free carrier densities and transport in this wide bandgap semiconductor. We used a combination of depth-resolved cathodoluminescence spectroscopy and surface photovoltage spectroscopy to identify the optical and energy-level properties of these defects as well as how their defect densities and spatial distributions vary with neutron irradiation and temperature-dependent-forming gas anneals. These studies reveal optical signatures that align closely with theoretical energy-level predictions. Likewise, our optical techniques reveal variations in these defect densities that are consistent with hydrogen passivation of gallium vacancies as a function of temperature and depth from the free Ga₂O₃ surface. These techniques can help guide the understanding and control of dominant native point defects in Ga₂O₃.

Ir is a common impurity in the edge-defined film-fed growth method used to produce high-power Ga₂O₃ device structures and growth substrates; yet, the effects of this deep level defect on carrier transport and recombination, particularly at high device processing and operating temperatures and at metal interfaces, have yet to be explored. The optical and electronic nature of Ir in Ga₂O₃ and at Ir/ Ga₂O₃ interfaces change on a near-nanometer to micrometer scale after nitrogen rapid thermal annealing; the understanding and control of which could lower defect-assisted tunneling, improve diode rectification, and preserve critical electric field strength. Depth-resolved cathodoluminescence spectroscopy, interface electronic current, and capacitance–voltage measurements reveal how this dominant impurity in bulk, edge-fed crystal growth diffuses, evolves with temperature, and impacts defect formation and Schottky barrier formation.