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Electron trapping effects in C- and Fe-doped GaN and AlGaN

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Abstract

Iron- and carbon-doped GaN and iron-doped $Al_{0.2}Ga_{0.8}N$ irradiated by low energy electron beam of scanning electron microscope were studied by cathodoluminescence and electron beam-induced current techniques. Irradiation is shown to induce a systematic decay of the cathodoluminescence intensity, which is accompanied by increased electronic carrier diffusion length, indicating the increase of carrier lifetime. Temperature-dependent cathodoluminescence measurements yielded activation energies for irradiation-induced effects of 210, 230, and 360 meV for GaN:C, GaN:Fe, and $Al_{0.2}Ga_{0.8}N$:Fe, respectively. These observations are consistent with trapping of non-equilibrium electrons on deep, non-ionized acceptor levels.
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1. Introduction

Due to their intrinsic thermal and electronic stability, wide bandgap semiconductors offer a significant advantage for high temperature, high power applications of both electronic and photonic devices. GaN compounds have been extensively investigated as good candidates for blue and UV opto-electronic devices, such as detectors and emitters, as well as high-power electronics. Additionally, high Curie temperatures and room-temperature ferromagnetism have been predicted in GaN-doped with transition-metal elements, such as Mn, Cr, and Fe, which in principle opens the door for room temperature, semiconductor-based spintronic applications.

The efforts to produce GaN-based materials with good n- and p-type conductivity, as well as with high resistivity for use in buffer layers, are driven by the notion that the quality of all-GaN devices is intrinsically superior to that of the heterojunction devices, optical and electronic properties of which are impeded by the lattice mismatch at the interface.

While magnesium remains the only feasible p-type dopant in GaN, numerous attempts have been made to introduce carbon as a shallow acceptor. These were motivated largely by the theoretical predictions that carbon, if substituted on nitrogen site, forms an acceptor level with ionization energy comparable to or lower than that of magnesium [1,2]. However, the same reports indicate that carbon is an amphoteric dopant, producing both donor and acceptor states in GaN. Evidently, relative concentrations of these states (and therefore, optical and transport properties of the resultant material) are strongly affected by the

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growth parameters: while some researchers succeeded in achieving p-type conductivity [3,4], others obtained either insulating or n-type material [5,6].

Although Fe is also known to form acceptor states in GaN, its 3+/2+ charge transfer level is located close to the bottom of the conduction band [7,8]. Therefore, studies of GaN:Fe are generally focused on goals other than obtaining a p-type material. Theoretical predictions have been made concerning the possibility of room-temperature ferromagnetism in transition metal-doped GaN [9], and a number of researchers report apparent ferromagnetism attributable to Fe doping ([10] and references therein). However, the success in this area is often limited by the insufficient carrier concentration arising from the deep nature of Fe acceptor state.

On the other hand, C- and Fe-doped GaN films are becoming increasingly popular in their highly resistive form for use as insulating buffer layers or substrates in GaN-based device technology. While nominally undoped GaN exhibits n-type conductivity, doping with impurities like C or Fe is known to induce deep acceptor states that compensate the residual donor concentration, resulting in highly insulating films with resistivity $> 10^8\ \Omega$ [6,11].

Resistive GaN buffer layers are the building blocks for AlGaN/GaN high electron mobility transistors (HEMTs). One of the major remaining challenges is to overcome current collapse associated with surface states and/or deep level traps in the bulk [11]. Mediating or controlling deep level states in the high resistivity GaN would lead to reproducible device performance.

The presence of impurity states deep within the bandgap has also been associated with a pronounced optical signature in GaN. Most studies focus on photo-induced changes of the blue (2.9 eV) and yellow (2.2 eV) luminescence bands. In nominally undoped GaN, the photoluminescence (PL) intensity of the yellow band is reported to increase, while the blue photoluminescence decays with duration of excitation [12–14]. It is noteworthy that these phenomena appear to be closely related to persistent photoconductivity (PPC) as well as optical quenching (OQ) of photocurrent, which makes the investigation of deep impurity states an issue of practical importance. The precise origin of the above behavior remains a subject of controversy, but evidence exists that the change in optical signature, as well as PPC and OQ, is caused by the metastable impurity-related carrier traps located in the bandgap [14,15].

Interestingly, the authors of the present work consistently observed somewhat different characteristics of metastability in *p-type* GaN and AlGaN, doped with Mg or Mn, induced by exposure to the beam of a scanning electron microscope (SEM). In all cases, the intensity of yellow band remained unchanged under electron beam excitation, while the near-band-edge (NBE) luminescence underwent a systematic decay [16,17]. Note that these observations were made above 200 K and therefore are not necessarily in contradiction with those discussed previously, since Ryan et al. [12] showed that above 150 K, the intensity of the yellow band is not significantly impacted by excitation, and that the blue band virtually disappears from the PL spectrum.

Moreover, the decrease in the intensity of the NBE transitions observed in p-type GaN and AlGaN was shown to be directly related to the multi-fold increase of minority carrier diffusion length (L), which indicates that electron irradiation enhances the lifetime of these carriers. Temperature-dependent measurements confirmed that the above-referenced observations are not only concomitant, but originate from the same phenomenon, i.e., trapping of non-equilibrium electrons on the deep acceptor levels [16,18].

A very practical consequence of increased minority carrier diffusion length is the improved carrier collection efficiency. It was shown that the peak responsivity as well as the spectral range of GaN-based photodetectors is dramatically enhanced by electron irradiation [19]. Furthermore, this improvement is known to persist for at least several days.

In this work, we present a cathodoluminescence (CL) study of electron irradiation-induced metastability of near-band-edge luminescence in insulating, C- and Fe-doped (Al)GaN and establish its relationship to the carrier diffusion length via electron beam-induced current (EBIC) measurements. Both observations are shown to be a consequence of increased carrier lifetime. Variable-temperature CL measurements are reported to provide further evidence for the involvement of deep electron traps in the irradiation-induced phenomena.

2. Experimental

High-resistivity carbon-doped GaN was grown on sapphire substrates by metalorganic chemical vapor deposition (MOCVD). Iron-doped GaN and $Al_{0.2}Ga_{0.8}N$ samples were prepared by molecular beam epitaxy (MBE). The thickness of the epitaxial layer was 3.4 μm for GaN:C and 1.5 μm for Fe-doped samples. Electronic carrier diffusion length was monitored in situ, in a Philips XL30 scanning electron microscope (SEM), using EBIC technique in planar Schottky contact configuration. Detailed description of EBIC technique, particularly as applied to monitoring electron irradiation-induced phenomena, can be found in [20–22] and references therein. Because of the highly compensated nature of GaN:C and GaN:Fe samples (carbon and iron concentrations amount to $\sim 5 \times 10^{19}\ cm^{-3}$), the carrier diffusion length determined from EBIC most likely represents the effective diffusion length for the non-equilibrium electron–hole pairs. EBIC measurements were performed at room temperature with electron beam accelerating voltage of 10 kV, corresponding to the electron penetration depth into the material of less than 1 μm. Local irradiation of the samples was carried out by the beam of the SEM with electron flux of $6 \times 10^{15}\ cm^{-2}\ s^{-1}$, corresponding to the energy flux of $\sim 10\ J/(cm^2\ s)$. After acquiring the first EBIC measurement from a single line-scan (about 12 μm of scanning length), the beam was scanned

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