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Photoelectric properties of highly excited GaN:Fe epilayers, zgrown by modulation- and continuous-doping techniques

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Abstract

Investigation of photoelectrical properties of iron modulation-doped (MD) and continuously doped (CD) GaN layers has been carried out by transient photo-Hall, photo-conductivity, and time-resolved picosecond four-wave-mixing (FWM) techniques. The MD semi-insulating (SI) layers exhibited prolonged photocurrent relaxation time and the presence of deep defects with thermal activation energy of 217 meV. Low electrical activity of threading dislocations (TD) in the upper part of the MD layers as well as high carrier mobility at low temperature was confirmed by FWM measurements and pointed out to vanishing dislocation-related heterogeneous barriers due to Fe doping. In contrast, shorter carrier lifetimes and low mobility in CD-layers were attributed to Fe-related defects, more "detrimental" centers than dislocations.

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1. Introduction

The efforts to produce highly resistive GaN materials are driven by need of insulating buffer layers which are the building blocks for III-nitride high electron mobility transistors (HEMT). Deep acceptor impurities, as C, Be, Mg, Zn or Fe (often together with the presence of a high dislocation density) can compensate the nominally undoped n-type conductivity and result in highly insulating layers [1,2]. However, the role of extended defects and doping-induced ones on electrical properties of semi-insulating (SI) templates needs further studies. Up to now, the photoluminescence [3] and cathodoluminescence [4] were the main techniques used to explore the deep defect states and their transformation under excitation.

A novel possibility to analyze fast electronic processes in a non-destructive "all-optical" way, i.e. without any electrical contacts, has been demonstrated in III-nitride semiconductors. The strong correlation between optical and electrical properties offers the possibility to monitor non-equilibrium carrier dynamics in a semiconductor with high spatial and temporal resolution, using time-resolved four-wave mixing (FWM) technique [5–7]. In this way, deeper insight into carrier recombination and diffusion features in non-intentionally doped (NID) GaN layers with different dislocation density was reached.

In this work, we extend investigation of photoelectrical properties in differently doped GaN:Fe layers, grown by metalorganic chemical vapor deposition (MOCVD) on sapphire substrates. In order to discriminate between the contributions of Fe-related defects and threading dislocations (TD) to the carrier recombination and scattering processes, we investigated iron modulation-doped (MD) and continuously doped (CD) layers and compared their

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properties with those in NID GaN layers with different dislocation densities. Interband photoexcitation by picosecond duration laser pulses allowed monitoring the carrier recombination and diffusion processes in few nanosecond time range, as the photoexcited carriers reside in a 1–2 μm thick surface region of the layer. Complementary techniques of photoconductivity and transient photo-Hall have been applied to study carrier density and mobility relaxation in microsecond time domain. The electrical activity of defects varying with Fe doping, temperature, and photoexcitation was analyzed and exhibited the improved photoelectrical parameters after modulation doping, while the continuous one resulted in more efficient carrier trapping.

2. Samples and techniques

Iron-doped GaN layers have been grown by low-pressure MOVPE using ferrocene as Fe precursor and double-sided polished sapphire. Continuous doping was carried on for growth of three GaN layers with different iron concentration in the range from mid-10^{17} to 10^{19} cm^{-3} [2]. The iron doping for material compensation was combined with the specific MOVPE process so-called "Si/N treatment" which lead to GaN layer with low threading dislocation density (in the low- to the mid-10^8 cm^{-2}) [2,8]. Nevertheless, even at the highest limit of Fe concentration tolerated in GaN material ($\sim 1.2\times10^{19}$ cm^{-3}), high resistivity was not reached by CD-doping (at most $3\times10^4\,\Omega$ was measured) [9]. The sheet resistance for iron-doped GaN layers dramatically increases to $\sim 10^9\,\Omega$ if more than 10^{20} Fe atoms/cm^3 are introduced only during the early stage of epitaxy, i.e. using the MD technique. In order to discriminate the contribution of Fe-related defects and the TD on the carrier recombination and scattering properties, we used one typical MD layer and three reference NID samples. Two of the NID layers were conductive with TD density N_{TD} in the range 2×10^8–2×10^9 cm^{-2}, and the third one was a SI, self-compensated due to a very high density of dislocations $N_{TD}=10^{10}$ cm^{-2}. Electrostatic force microscopy method, used to measure carrier in-depth profiles, showed that the iron compensation effect is effective only while GaN deposition is in a facetted mode (early stage of epitaxy) and so is most prominent in MD layers [2]. The parameters of the iron-doped and reference samples are listed in the Table 1.

For photoconductivity and Hall measurements, indium contacts were positioned on the corners of square-shaped samples. Hall measurements were carried out in a $B=1.7$ T magnetic field, and the applied electric field value varied up to $E_x \leqslant 100$ V/cm. 7 ns duration pulses at 355 nm wavelength were used for photoexcitation, and the electrical circuit provided 100 ns resolution. Carrier concentration was estimated from the Hall voltage and electric current data, and the measurements in 100–400 K range provided trap activation energy. The Hall mobility was calculated using ratio $\mu_H = E_H/(E_x B)$, with E_H as the Hall field and taking the Hall factor equal to 1.

The time-resolved picosecond FWM technique [5,6] has been applied for the investigation of nonequilibrium carrier dynamics in wide temperature range (10–300 K) at interband excitation ($h\nu = 3.49$ eV). A spatially modulated nonequilibrium carrier distribution $N(x)=\Delta N[1+\cos(2\pi x/\Lambda)]$ with period Λ varying from 4 to 15 μm was recorded by light interference pattern of two 25 ps duration laser beams. The decay of light-induced free carrier grating was monitored in 2 ns time domain by the diffraction of a delayed probe beam at 1064 nm. The grating diffraction efficiency η nonlinearly responds to instantaneous carrier density modulation ΔN (i.e. $\eta \propto \Delta N^2$), thus grating decay kinetics $\eta(t) \propto [\Delta N_{t=0}\exp(-t/\tau_G)]^2$ provides its decay time τ_G at various period Λ. The carrier lifetime and diffusion coefficient were determined by using a simple relationship $1/\tau_G = 1/\tau_R + 1/\tau_D$, where $\tau_D = \Lambda^2/4\pi^2 D$ is the diffusive grating decay time, and τ_R is the average carrier lifetime in the excited region, governed by nonradiative and radiative recombination.

3. Results and discussion

3.1. Photoconductivity and transient hall measurements

The summarized results of photoconductivity and transient Hall measurements are presented in Table 2. Electric field-dependent Hall mobility provided information about non-homogeneity of the samples. Sample NID2 (no Fe doping; medium N_{TD} value) revealed the presence of a deeply located conductive layer, which was attributed to crystal imperfections like higher background impurities or vacancies and complexes. In CD samples, the given effect disappeared with doping, leading to a homogeneous conductive layer. It was also observed that in NID2 layer

Table 1
Electrical and doping parameters of the investigated samples

Sample code	NID1	NID2	NID3	MD	CD1	CD2	CD 3
Fe density, at/cm^3	~None	~None	~None	5×10^{16} near surface	9×10^{17}	2×10^{18}	8×10^{18}
Electrical behavior	Cond.	Cond.	SI	SI	Cond.	Cond.	Cond.
TD density, cm^{-2}	~(2–5) $\times10^8$	2×10^9	10^{10}	~(5–8) $\times10^8$	3×10^8	3×10^8	~5×10^8
Thickness, μm	**~3**	2.3	2.8	5.9	3.2	3	3.1
Sample label	L189/190	T1130	T1133	T1100	T1143	T1131	T1101