In situ time-resolved synchrotron radiation nanobeam X-ray diffraction analysis of inverse-piezoelectric-effect-induced lattice deformation in AlGaN/GaN high-electron-mobility transistors

Gallium nitride (GaN) is expected to be used as an alternative material for power electronic devices owing to its superior physical properties of higher breakdown voltages and greater thermal stability than Si. In particular, AlGaN/GaN high-electron-mobility transistors (HEMTs) have attracted considerable attention for use in high-frequency and high-power operations. As a characteristic of group III nitride semiconductors, a polarization-induced two-dimensional electron gas (2DEG) is introduced at the AlGaN/GaN interface, where both the effects of the spontaneous polarization difference and the piezoelectric polarization produced by the lattice mismatch strain between AlGaN and GaN contribute to the high-concentration 2DEG. Although such piezoelectricity occurring in an AlGaN/GaN HEMT gives rise to a high current density, it has been reported that the inverse piezoelectric effect (IPE) can also cause deterioration in the device performance through the inhomogeneous distribution of strain and the formation of defects in the localized area of the device. Knowledge of the local IPE, especially during device operation, is indispensable for precisely controlling the piezoelectric properties; however, an appropriate measurement technique for the piezoelectric properties has not yet been fully established.

Diffraction is an effective tool for directly observing lattice structures and clarifying the process of defect formation that adversely affects the properties of crystalline materials and the performance of devices. The observation of lattice distortion in piezoelectric materials such as lead zirconate titanate under an applied voltage using time-resolved stroboscope X-ray diffraction techniques in previous studies has been reported [1]. Compared with the piezoelectric constants of these piezo compounds, those of AlGaN or GaN are two orders of magnitude smaller. Thus, the observation of IPE-induced lattice deformation in AlGaN and GaN using diffraction techniques is challenging.

In this work, we developed an *in situ* measurement system based on a synchrotron radiation nanobeam X-ray diffraction (nanoXRD) technique combined with a pump-probe method to investigate local lattice deformation in operating nitride devices [2]. By utilizing synchrotron radiation X-ray pulses with very small widths, we observed the dynamic behavior in the process of lattice deformation with a high time resolution on the order of nanoseconds. We quantitatively investigated the local lattice deformation of an AlGaN barrier layer caused by the IPE in an AlGaN/GaN HEMT device under an applied gate voltage.

A schematic of the sample device structure used is shown in Fig. 1(a). The sample was an AlGaN/GaN MOS-HEMT device [3]. The thickness and Al content of the AlGaN barrier layer were 20 nm and 20%, respectively. The diffraction geometry is shown in Fig. 1(b). The synchrotron X-ray beam (200 nm × 500 nm) focused by a zone plate at SPring-8 **BL13XU** was used for the experiments. The X-ray nanobeam was incident on the gate electrode from the *m* direction to obtain the AlGaN 0004 diffraction as a gate voltage was applied to the device. Three-dimensional (3D) ω–2θ–φ mapping was performed for the diffraction [4]; to quantify the 2θ value corresponding to the lattice spacing, the measured 3D diffraction profiles were integrated over the ω (lattice tilting) and φ (lattice twisting) directions to obtain one-dimensional 2θ profiles. In the pump–probe experiments, we applied a gate voltage as a pump pulse that was synchronized with the X-ray irradiation as a probe pulse and changed the phase of the voltage pulse with respect to the X-ray pulse.

Figures 2(a) and 2(b) show AlGaN(0004 2θ profiles recorded under static negative gate voltages from 0 to −7 V and positive voltages from 0 to +7 V, respectively. The 2θ profiles and peaks clearly shifted to lower angles with negatively increasing voltage, whereas no marked shifts were observed when a positive voltage was applied. Figure 2(c) shows the gate-voltage dependence of the AlGaN *c*-plane lattice spacing calculated from the 2θ profile using a Bragg equation. We observed that the lattice spacing increases linearly with the applied negative gate voltage. This behavior is quantitatively consistent with the piezoelectric response estimated from the exerted electric field on the AlGaN layer and piezoelectric coefficients as well as the clamping effect from the substrate.

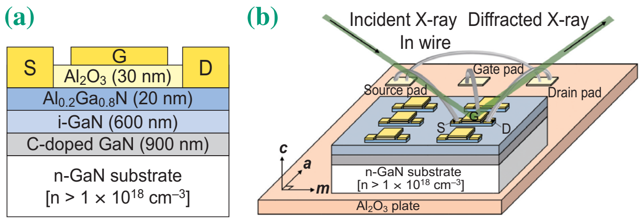

Fig. 1. **(a)** Schematic of the AlGaN/GaN MOS-HEMT device structure characterized in the present study and **(b)** schematic of the diffraction geometry in which the source and drain electrodes of the device are equipotential with In wire (S, source; G, gate; D, drain).

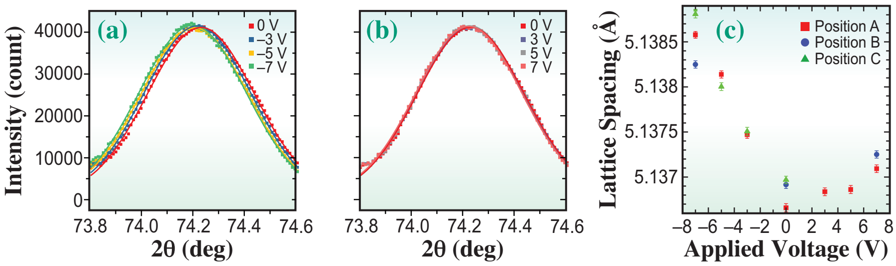

Fig. 2. Observed AlGaN 0004 diffraction 2θ profiles for **(a)** negative and **(b)** positive applied gate voltages. **(c)** Gate-voltage dependence of the AlGaN (0001) lattice spacing derived from the 2θ profile peaks.

Further dynamic measurements of AlGaN strain responses were performed using the application sequence for X-rays and gate-voltage pulses shown in Fig. 3(a). For the dynamic analysis, the single-bunch (SB) section of the hybrid-bunch mode was selectively used by employing an X-ray chopper device [5] and 60-ps-wide X-ray pulses were emitted at an arbitrary delay time during the application of the gate voltage pulse. Figures 3(b) and 3(c) show the variations in AlGaN *c*-plane lattice spacing as a function of the delay time during the application of the gate voltage for pulse-width and edge-time dependences, respectively. In all cases, we observed that the lattice spacing started to increase at the onset of voltage application to a certain value less than ~5.1385 Å and then decreased to the initial value of ~5.137 Å at the end of the voltage application. The present results successfully revealed the dynamic behavior of the *c*-plane lattice spacing change due to the IPE caused by the applied gate voltage on the nanosecond time scale. Interestingly, these lattice-spacing variations show a time lag following the application of voltage; this time lag is on the order of tens to hundreds of nanoseconds, depending on the pulse width and edge time, and was attributed to the voltage drop due to transient current. This nanoscale time-resolved analysis revealed the effect of transient current flowing in the device on the lattice deformation response during the application of a gate voltage.

In summary, we developed a measurement system that can perform detailed analyses of IPE-induced lattice deformation in an AlGaN/GaN HEMT device via synchrotron radiation X-ray diffraction combined with the pump-probe method. The present results are enlightening in that high-time-resolution strain analysis revealed that seemingly stationary nitride semiconductor devices actually experience significant dynamic deformations under their operating conditions. An extended nanoXRD-based analysis with high spatial and temporal resolutions will provide further details of local dynamic strain behaviors related to device structures or lattice defects in nitride semiconductors.

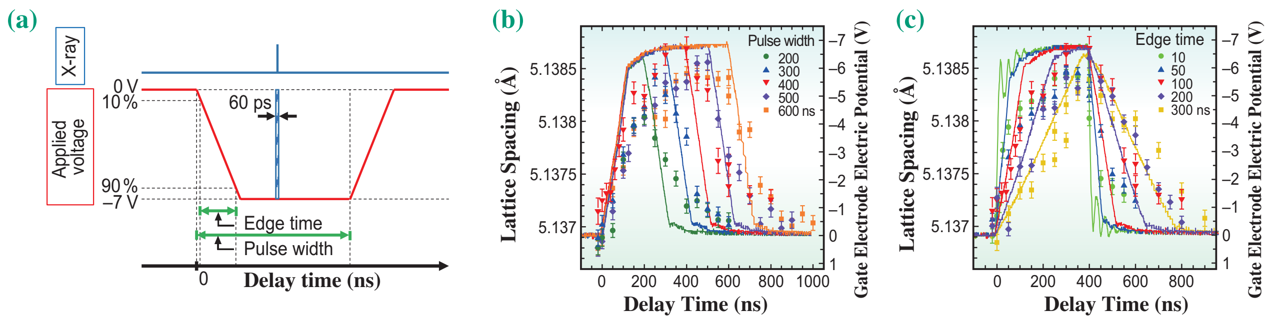

Fig. 3. **(a)** Application sequence of X-ray and gate-voltage pulses in the measurements. Time dependence of the AlGaN (0001) lattice spacing (left axis, color plot) and the measured electric potentials of the gate electrode (right axis, color line) for **(b)** pulse-width and **(c)** edge-time dependences of the gate-voltage application.

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