Impact of *operando* X-ray spectromicroscopy for constructing Beyond 5G toward the realization of Society 5.0

5G is the current wireless communication technology that connects things and humans via cyberspace, and is being rapidly introduced into our lives owing to the COVID-19 pandemic. The next-generation wireless communication, Beyond 5G, seamlessly connects things, humans, and matter. Beyond 5G serves as the fundamental infrastructure of the forthcoming Society 5.0, which will incorporate the effective solutions for attaining sustainable development goals (SDGs) that were adopted at the United Nations sustainable development summit. Domestically, wireless communication is one of the last scientific and technology fields in which Japan maintains global competitiveness, and it accounts for 10% of its GDP. For instance, Sumitomo Electric Industries succeeded in commercializing GaN-based high-electron-mobility transistors (GaN-HEMTs) using two-dimensional electron gas (2DEG) formed at the AlGaN/GaN interface for the first time and boasts the world's top share. For Beyond 5G, more than a trillion devices are anticipated to be always-on in Japan. Possible candidates of Beyond 5G devices will utilize high-environmental-load elements, such as As, In, and Cu. Therefore, we should expend much effort to reduce the environmental load of Beyond 5G. For this purpose, low-environmental-load materials consisting of, for example, C, B, N, and Ga, which have excellent electronic properties, such as graphene, the AlGaN/GaN interface, and the two-dimensional boron-based layer (borophene) should be used for Beyond 5G devices. The frontier in material sciences is hence the realization of the full potential of low-environmental-load materials.

Among low environmental-load devices, GaN-HEMTs are promising for Beyond 5G base-station communication. This is because GaN-HEMTs operate at high frequencies up to around 200 GHz with a high output owing to a high electron mobility and a large bandgap. However, one critical issue, that is, current collapse phenomenon, must be resolved to enable stable long-period device operations (Fig. 1) [1]. The current collapse phenomenon is a significant reduction in output drain current upon applying high voltage stresses during the operation of GaN-HEMTs. The current collapse phenomenon has been suggested to originate from surface electron trapping near the gate electrode on the drain side. The surface electron trapping is induced by a large local electric field due to the high voltage stresses, i.e., the large bias applied to the gate and drain electrodes. The mechanism of surface electron trapping has not been clarified in detail because conventional macroscopic electric measurements and scanning probe microscopies cannot reveal the surface and interface properties site-specifically or element-selectively.

To elucidate device operation mechanisms in detail, we developed *operando* X-ray spectromicroscopy under bias application [2,3]. In fact, we demonstrated that *operando* X-ray spectromicroscopy is a powerful tool for elucidating operation mechanisms of cutting-edge devices owing to the site specificity and element selectivity that enable the information of target materials, i.e., Ga atoms, to be distinguished from that of carbon contaminants.

First, we applied *operando* X-ray photoelectron spectromicroscopy on GaN-HEMTs to precisely elucidate the mechanism of surface electron trapping under DC bias at SPring-8 **BL07LSU** [4]. Contrary to the previous suggestion base on macroscopic electrical measurements that surface electron trapping occurs near the gate electrode on the drain side [1], it was found that surface electron trapping occurs both near the gate electrode on the drain side and near the drain electrode. This result indicates that the mechanism of surface electron trapping under DC bias is different from that under non-DC bias in the actual operation of GaN-HEMTs. We then speculated that surface electron trapping changes spatiotemporally.

To verify this speculation, we carried out an experiment of spatiotemporally resolved *operando* X-ray absorption near edge structure (ST-XANES) of the Ga L_3 edge using the photoemission electron microscope (PEEM) at SPring-8 **BL25SU**, as shown in Fig. 2(a). The experiment involves tuning the pulsed X-ray radiation, illuminating an entire sample, and imaging the spatial variation of the yield of subsequently emitted Auger electrons. The incident X-ray is absorbed owing to the excitation of an electron in a core level to unoccupied states. The hole in the core level resulting from this absorption process can then be filled by an

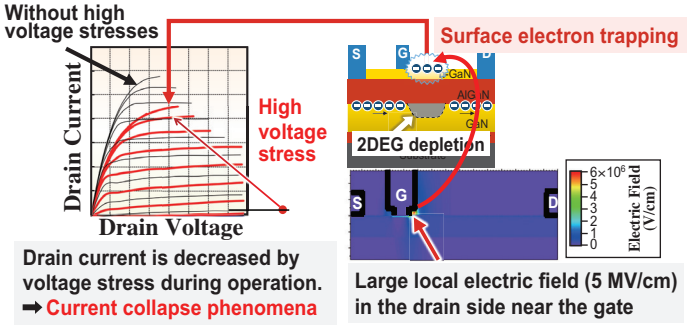

Fig. 1. Schematic of current collapse phenomenon in GaN-HEMT, originating from surface electron trapping.

outer electron falling into the core level. The resultant excess energy is channeled into the ejection of Auger electrons. By collecting the Auger electrons, with the help of PEEM, as a function of the incident X-ray energy and the delay time relative to the bias voltage pulses, we obtained ST-XANES spectra. To simultaneously achieve a high temporal resolution, soft X-ray pulse trains (train width: 1.813 μs) were extracted using an X-ray chopper with 220 μs intervals. The bias voltage pulses (gate: –5 V, drain: 30 V, pulse width: 4 μs) were synchronized with the X-ray pulse trains. The ST-XANES measurement using the pulsations of X-ray and bias voltages was repeated 25000 times to obtain ST-XANES spectra and ensure statistical accuracy.

It was found that peak A of the ST-XANES spectrum near the gate electrode on the drain side immediately (1 μs) after switching off the bias application changed, as shown in Fig. 2(a). According to the previous theoretical work [6], the weakening of peak A indicates an increase in the covalency of the Ga–N bond. The explanation for this is that donorlike surface states, i.e., positively charged Ga atoms, accept electrons, leading to the neutralization of the surface states. Hence, the neutralized surface states exist only near the gate electrode on the drain side. As shown in Fig. 2(b), it can be concluded that surface electron trapping occurs only near the gate on the drain side because of the large local electric field with a short-period bias application (ps–ns), as observed in this work [5]. This is followed by the hopping of the surface-trapped electrons to the drain electrode, as observed in our previous work [4]. By comparing the result of this work with those of high-frequency electrical characterization, the surface electron trapping was demonstrated to markedly affect the paramount figure of merit, that is, the cutoff frequency, which is the upper limit frequency of current amplification.

In summary, to contribute to the realization of low-environmental-load Beyond 5G, we have succeeded in directly observing the spatiotemporal dynamics of surface trapping in GaN-HEMTs by using spatiotemporal *operando* X-ray spectroscopy and newly proposing a new mechanism of surface electron trapping. Note that our findings cannot be obtained by conventional electrical characterization and non-element-specific scanning probe microscopies. Considering the timescale of the bunch mode and X-FEL, we believe that SPring-8 is the core facility for exploring new physics appearing in millimeter-wave and THz-frequency regions, where carriers in materials move at the critical speed, and Beyond 5G developments for realizing Society 5.0 and attaining SDGs.

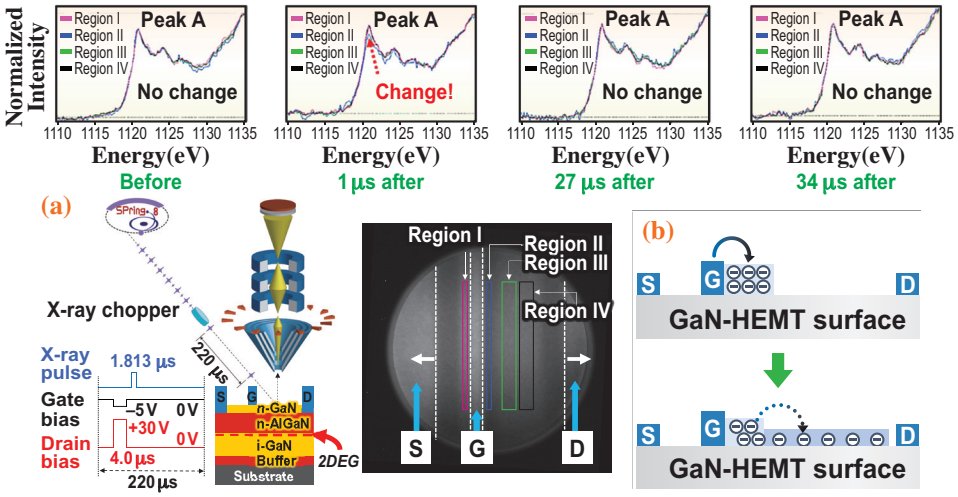

Fig. 2. **(a)** Spatiotemporal observation of surface electron trapping in GaN-HEMT using spatiotemporal *operando* X-ray absorption spectroscopy and schematics of the experimental system. **(b)** Proposed mechanism of surface electron trapping based on results of DC *operando* X-ray photoelectron microscopy and spatiotemporal *operando* X-ray absorption spectroscopy. S, G, and D indicate the source, gate, and drain electrodes, respectively.

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