Study of temporal relaxation of surface photovoltage effect on InN surfaces

C.-H. Lin, R. Yukawa, S. Yamamoto, R. Hobara, I. Matsuda, and S.-J. Tang

1. *Department of Physics and Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan*
2. *Institute for Solid State Physics, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan*

Indium nitride InN is a semiconductor with a narrow band gap ~0.7 eV, which has drawn a lot of attention for applications in high efficiency solar cells and high-speed electronic devices. The key issue for understanding InN-based device applications has been proposed to be correlated to the unusual phenomenon of strong electron accumulation and downward band bending at as-grown InN surfaces, no matter N-polar or In-polar [1]. Leyla Colakerol *et al.* [2] found the electrons in the accumulation layer of InN to exist in the discrete quantum well states derived from conduction band. Nevertheless, Kuo *et al.* [3] discovered the flat band from N-polar InN surface through the combined treatment of ex situ chemical wet etching and in situ annealing. On the other hand, surface photovoltage (SPV) effect on semiconductor surfaces has been a center of interest due to its close relation to photovoltaic and photocatalytic mechanisms that directly lead to solving several of global energy issues [4].

We study the SPV effect on various InN surfaces characterized with different polarities or different electronic conditions with highly downward band bending or flat band using high resolution time-resolved photoemission spectroscopy at beamline BL07LSU in SPring-8. InN has strong surface electron density in the accumulation layer and its narrow band gap would enhance the generation of electron-hole pairs through the photon excitation, which is the key for SPV effect. We expected SPV effects from differently characterized InN surfaces would exhibit distinct and interesting features. It needs to note that Prof. Iwao Matsuda's group recently discovered surprising oscillatory relaxation of SPV effect on a *n*-typed highly-doped Si(111)-7x7 surface [5,6] with the upward surface band bending, induced by the laser of high power density, and the correlation of two different relaxation mechanisms to different characterized Si surfaces [7] . It is extremely interesting to study the corresponding behavior of this *p*-typed InN surface with downward surface band bending.

In the last beamtime at beamline BL07LSU in SPring-8 (Oct.22 2013 – Oct.25 2013), we carried out the experiment on the N-polar InN surface with downward band bending. We discovered the time-resolved behavior completely distinct from that expected from a SPV picture. Figure 1(a) shows the energy shift of In 4*d* core level as a function of delay time at a fixed laser power 8 μW. As opposed to the behavior that the energy shift would eventually decrease back to zero, the energy shift increase in negative direction initially and then turns to change largely in positive direction over longer time scale up to 10 ns. It appears that there are two different mechanisms competing with each other after the formation of electron-hole pair, excited by the pumped laser. Actually InN itself, with its narrow gap of 0.7 eV, is a degenerate semiconductor, in the space charge layer, in which Photo-Dember effect dominates. This effect has been well known to be responsible for generating terahertz light. Usually, there are two photovoltage effects at a semiconductor surface, surface photovoltage effect (drift-induced) and Photo-Dember effect (diffusion induced). And the surfaces of semiconductors with narrow band gaps are more akin to the latter. The result of last beamtime indicates a great opportunity to depict the complete time-resolved behavior of Photo-Dember effect from InN surfaces by the high- resolution time-resolved photoemission for the first time. We have carried out the simulation research to study the detailed dynamics of the carriers on the InN surface. Currently, we obtained simulation results at the initial stage (picoseconds-time scale) that indicates the photo-Dember effect, as shown in Fig.1(b). In order to understand the whole relaxation picture (nanoseconds-time scale), much data from the time-resolved photoemission experiments is highly called for.

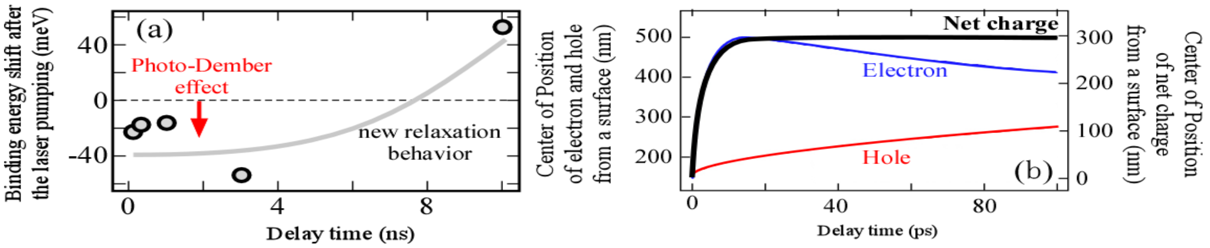

Fig.1: (a) The energy shift of In 4d core level as a function of delay time at the pumping laser power of 8 μW and (b) numerical simulation results on an InN surface: more holes at surface and more electrons in the bulk, indicating the photo-Dember effect.

REFERENECS

[1] I. Mahboob, *et al.*, Phys.Rev. Lett. **92**, 036804 (2004).
[2] Leyla Colakerol *et al.*, Phys. Rev. Lett. **97**, 237601 (2006).
[3] C.-T. Kuo *et al.*, Appl. Phys. Lett. **98,** 052101 (2011).
[4] N. Sangouard *et al.*, Rev. Mod. Phys. **83**, 33 (2011).
[5] M. Ogawan *et al.*, Phys. Rev. B **87**, 235308 (2013).
[6] M. Ogawa, *et al.*, Surf. Sci., **624**, (2014), 70-75.
[7] M. Ogawa *et al.*, Phys. Rev. B **88**, 165313 (2013).