Imaging Field-Induced Metastable DX Center Formation in Near-Surface Region of *n*-type InAs by Scanning Tunneling Microscopy

K. Kanisawa
Basic Research Laboratories, NTT, Inc., Japan

Control of semiconductor nanostructures becomes more important to achieve the further device miniaturization [1, 2]. Especially, critical significance of charge and spin states becomes evident at atomic-scale precision [3, 4]. Donor-related defect-complex, DX center, in III-V semiconductors is one of lattice defects. Charge states of this defect as well as the bistable switching on the long lifetime were studied for Si-doped *n*-GaAs [5, 6]. In the case of InAs, static transition of acceptor charge states in Mn-doped *p*-InAs is only reported [7].

In this presentation, the DX center in the near-surface region of *n*-type InAs is demonstrated as a quasi-equilibrated metastable state by using the scanning tunneling microscope (STM). After obtaining the cleaved (110) surface of sulfur-doped *n*-InAs (N_S : 4×10^{17} cm^{-3}) in ultra-high vacuum, the sample was transferred to the STM stage kept at 77 K. First, it is found that donor charge states showed striking dependence on the STM tip at the same scan condition. This suggests that the degree of the tip-induced band bending plays the crucial role of the charge state determination. Second, it is found that electrons tunneled from the STM tip cause an impact-ionization by the tip-induced electric field acceleration at the sample bias voltage $V > 0$ (tip is neutral). When the electric field exceeds the Avalanche breakdown field (～8×10^{-5} V/nm) [8], such hot electrons cause the impact-ionization. Generated secondary electrons are spread by radially diverging tip-induced field. At this non-equilibrium situation, the electron quasi-Fermi level becomes locally dominant to charge states of donor-related defects [9] beneath the tip. This quasi-Fermi level effect is detected as the bias voltage dependent topography. No evident bistable switching among charge states is imaged. These suggest that the imaged DX center in the *n*-InAs is a quasi-equilibrated metastable state available at the non-equilibrium condition and the lifetime of the captured electron by such DX center is expected much shorter than that of *n*-GaAs.

[1] S. Fölsch, J. Yang, C. Nacci, and K. Kanisawa, Phys. Rev. Lett. **103**, 096104 (2009).
[2] S. Fölsch, J. Martínez-Blanco, J. Yang, K. Kanisawa and S. C. Erwin, Nat. Nanotech. **9**, 505 (2014).
[3] P. M. Koenraad and M. E. Flatté, Nat. Mater. **10**, 91 (2011).
[4] J. Yang, S. C. Erwin, K. Kanisawa, C. Nacci and S. Fölsch, Nano Lett. **11**, 2486 (2011).
[5] K. Teichmann, M. Wenderoth, S. Loth, R. G. Ulbrich, J. K. Garleff, A. P. Wijnheijmer and P. M. Koenraad, Phys. Rev. Lett. **101**, 076103 (2008).
[6] E. P. Smakman, P. L. J. Helgers, J. Verheyen, P. M. Koenraad and R. Möller, Phys. Rev. **90**, 041410(R) (2014).
[7] F. Marczinowski, J. Wiebe, J.-M. Tang, M. E. Flatté, F. Meier, M. Morgenstern and R. Wiesendanger, Phys. Rev. Lett. **99**, 157202 (2007).
[8] G. Bauer and F. Kuchar, Phys. Lett. A **30**, 399 (1969).
[9] M. Asche and O.G. Sarbey, Physica B **308-310**, 788 (2001).

[+] Author for correspondence: kiyoshi.kanisawa@ntt.com

Suplementary Pages (Optional)

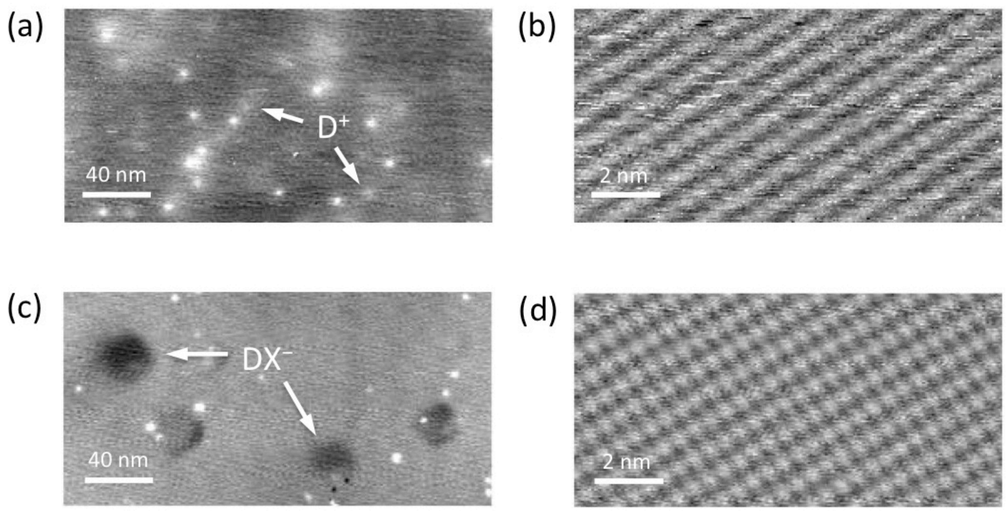

Fig. 1 STM topographies taken at different two positions of the same cleaved *n*-InAs(110) surface at 77 K. All images are taken at the same condition: bias voltage V = +1.6 V, tunnel current I_t = 5.0 nA. (a) donor at the near-surface region (shown by an arrow) is detected positively charged. (b) magnified image of the center of (a) to confirm the tip apex atomically sharp. (c) another position more than few microns away from the position (a). donor at the near-surface region detected negatively charged with forming a DX center (shown by an arrow). (d) magnified image of the center of (c) to confirm the tip apex atomically sharp. Since (b) and (d) show that the STM tip gets through the atomic resolution requirement, this striking characteristic difference of donor charge state is due to the geometric shape transition of tip apex (sharp or blunt) as experiment goes by. Moreover, it is not reasonable to assign this difference between (a) and (c) only to the tip-induced band bending (TIBB). It is because that (1) these charge state difference of donors is detected not at the topmost bare surface but in the near-surface crystal region, and that (2) the diameter of charge state transition boundary at each darker area around the near-surface DX^- in (c) is in the order of 10 nm, which scale is roughly ten times as large as that at each brighter area around the near-surface D^+ in (a). This large boundary diameter difference is not seen in ref. 6, which attributes the origin of charge state transition just to TIBB.

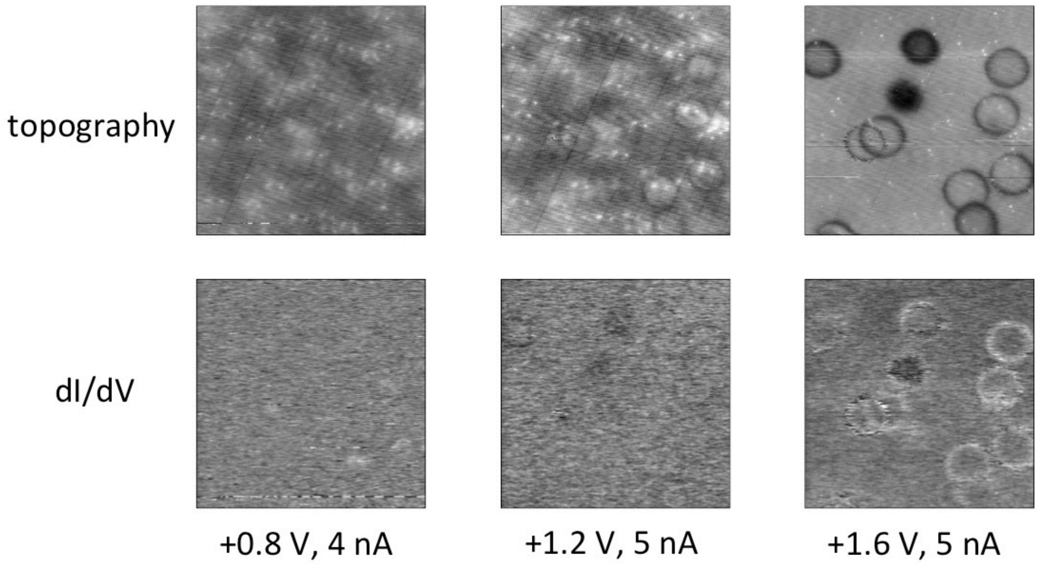

Fig. 2 Bias voltage dependence of STM topography and the corresponding dI/dV signal map at the same position (300 nm × 300 nm) at 77 K. As the voltage is increased, donor charge state shows a gradual transition from +1 (D^+) to -1 (DX^-). Boundaries of circular dark patterns in the topography at +1.6 V reflect the symmetry of the STM tip apex geometry and the effective length scale of the impact-ionization to the charge state transition. The bright circular patterns in the dI/dV map show that prominent inelastic tunneling process is activated in the very close vicinity of donors, when the stimulated charge state transition becomes evident.