Optical probe of electrostatic-doping in an n-type Mott insulator

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Success of carrier doping into a new class of insulators or by a new method has always marked a major breakthrough in material science and technology. Carrier doping into Ge and Si by chemical substitution made it possible to fabricate diodes and transistors and created the era of semiconductor technology. Then, carrier doping into semiconductors by electric field was realized and field-effect transistors (FET's) were fabricated; Now FET's constitute the majority of semiconductor circuits and are also the stage of fascinating basic physics. As for transition-metal oxides, through chemical doping Mott insulators with charge carriers, high-temperature superconductivity emerges in cuprates and colossal magnetoresistance in manganites. Therefore, electric field doping into Mott insulators has been eagerly anticipated and in fact have been attempted extensively by a number of research groups. However, field doping has been difficult for Mott insulators because much higher carrier densities are necessary than in conventional semiconductors to induce interesting physical phenomena [1]. Technical difficulties such as leakage current have hindered doping levels sufficient to induce the remarkable properties mentioned above. Meanwhile, a sufficiently high density of carriers were doped by electric field to induce insulator-to-metal transitions in oxide semiconductors, namely, in ZnO thin films using electrolyte gates [2] and at $LaAlO_3/SrTiO_3$ interfaces using atomic microscope (AFM) tips [3].

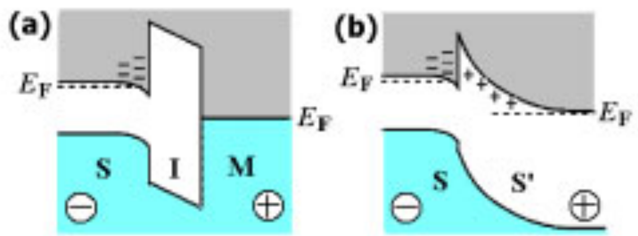

Figure 1: Schematic band diagrams of field effect devices. (a) Metal-inslator-semiconductor (MIS) structure; (b) Isotype heterojunction between an n-type Mott insulator (S) and an n-type semiconductor (S'). Positive bias is applied on the right-hand side of the interface, and in the case of (b), light is transmitted from left to right.

To overcome the leakage current problem, Nakamura and co-workers utilized an *isotype* heterojunction between an n-type Mott insulator and an n-type oxide semiconductor instead of the conventional metal-insulator-semiconductor gate structure, as schematically depicted in Fig. 1. The n-type Mott insulator [S in Fig. 1(b)] was Sm_2CuO_4, the parent compound of electron-doped cuprate superconductors, and the n-type semiconductor [S' in Fig. 1(b)] was Nb-doped $SrTiO_3$. In the isotype heterojunction, charge carriers (electrons in this case) are transferred across the interface depending on the work-function difference. The application of reverse bias enhances the amount of transferred charges. They fabricated a device which transmits light through the interface and monitored field-induced changes in the optical absorption spectra. The observation of field-induced spectral weight transfer from high to low energies unabiguously indicated that charge carriers were doped doped by the electric field. The amount of doped carriers went up to ~6 % for the gate voltage of 10 V. Unfortunately, carrier concentrations over ~15 % are needed for the superconducting phase to win the antiferromangetic phase in the electron-doped cuprates. Therefore, an obvious next challenge would be to apply the same technique to a p-isotype heterojunction, where superconductivity may be realized above ~5 % doping.

There are a lot of scientific opportunities in the field doping. One of them is to pin down the effect of disorder in strongly correlated systems. Since field doping does not introduce additional disorder, comparison with chemical doping will give us much insight. (Nakamura *et al.*'s optical spectra are already quite suggestive.) In the case of cuprates, because the effect of disorder on the phase diagram in the lightly-doped region have been quite controversial, further development of field doping in near future is strongly anticipated.

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[2] H. Shimotani, H. Asanuma, A. Tsukazaki, A. Ohtomo, M. Kawasaki and Y. Iwasa, Appl. Phys. Lett. **91**, 082106 (2007).
[3] C. Cen, S. Thiel, G. Hammerl, C. W. Schneider, K. E. Andersen, C. S. Hellberg, J. Mannhart and J. Levy, Nat. Mater. **7**, 298 (2008).