First Demonstration of Two-Dimensional WS_2 Transistors Exhibiting 10^5 Room Temperature Modulation and Ambipolar Behavior

Wan Sik Hwang[1], Maja Remskar[2], Rusen Yan[1], Vladimir Protasenko[1], Kristof Tahy[1], Soo Doo Chae[1], Huili (Grace) Xing[1], Alan Seabaugh[1], and Debdeep Jena[1]

[1]Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA
[2]Solid State Physics Department, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia

Spurred by the knowledge of isolation of graphene, other 2D transition-metal dichalcogenide materials in the form of MX_2 (where M=transition metal such as Mo, W, Ti, Nb, etc. and X=S, Se, or Te) have drawn considerable attention. The MX_2 family material consists of one or more sets of triple layers with one M and two X in a sandwich structure (X-M-X). Atoms within each layer are strongly held together by covalent-ion mixed bonds, while interlayer van der Waals forces are weak. Prior investigations of 2D materials have concentrated on optical properties [1]. Field-effect transistors (FETs) in MoS_2 and WSe_2 have been demonstrated with substantial gate modulation and stable current saturation [2, 3]. A recent calculation shows that the single layer WS_2 has the potential to outperform Si and other 2D crystals in FET-type applications due to its favorable bandstructure [4]. No prior device results have been reported for WS_2 for logic or optical devices. Here we report the first fabrication and demonstration of 2D WS_2 FETs and explore the effects of photosimulation on the transistor characteristics.

A schematic cross section image of the back-gated WS_2 device is shown in Fig. 1(a). The source and drain contacts are defined by electron beam lithography (EBL) using Ti/Au (5/100 nm) contacts. The optical image of the WS_2 device with L/W = 2.5/5 μm is shown in Fig. 1(b). The Raman spectra (λ = 488 nm) of the WS_2 region shown in Fig. 1(c) shows two peaks: one in the E_{2g}^{1} range at ~356 cm^{-1} and the other in the A_{1g} range at ~421 cm^{-1}. The 2D Raman signal is fit to two single Lorentzian models, revealing that the chemical vapor deposited (CVD) 2D WS_2 retains the single crystal properties of WS_2 with unnoticeable structural modifications. The energy band line-ups of Fig. 1(d) indicate that the Fermi level of the contact metal is aligned in the band gap of WS_2. Figure 2(a) shows drain current versus gate-source bias, I_D *vs.* V_{GS}, at room temperature for a multilayer WS_2 FETs at two drain biases. The gate modulation is ~10^5× for V_{DS} =1 V, and ~10^4× for V_{DS} =5 V. The device shows clear ambipolar behavior indicating accumulation of electrons (*n*-type conductivity) for positive V_{GS} and of holes (*p*-type conductivity) for negative V_{GS} regions. Thus, electrons or holes are preferentially injected depending on the gate bias as illustrated in Fig. 2(b) and 2(c), as a consequence of the Schottky contacts. This is seen clearly in the family of I_D - V_{DS} curves in Fig. 2(d). The photoresponse of the WS_2 Schottky barrier FETs was measured by illuminating the device with a halogen lamp; the result is shown in Fig. 3(a). The image of Fig. 3(b) shows a schematic representation of electron-hole pair generation upon photon absorption, and the increase of drain current due to conduction by these excess carriers. We observe that the saturation drain voltage increases under illumination which can be attributed to the photogeneration of carriers which require greater drain voltage to achieve pinch-off in the channel near the drain. Figure 3(c) shows multiple cycles of the transient photocurrent response under monochromatic illumination at two wavelengths, corresponding to photon energies of 2.1 eV (580 nm) and 1.9 eV (650 nm), both of which are above the expected bandgap of monolayer WS_2 (~1.8 eV).

In summary, two-dimensional (2D) WS_2 transistors were fabricated and characterized for the first time from chemically-synthesized material. Raman measurements confirm the 2D crystal nature of the material, and the presence of a bandgap leads to high on/off current ratios and current saturation in the transistors at room temperature. In addition, the observed photoresponse of the 2D layered semiconductor can enable optical device applications.

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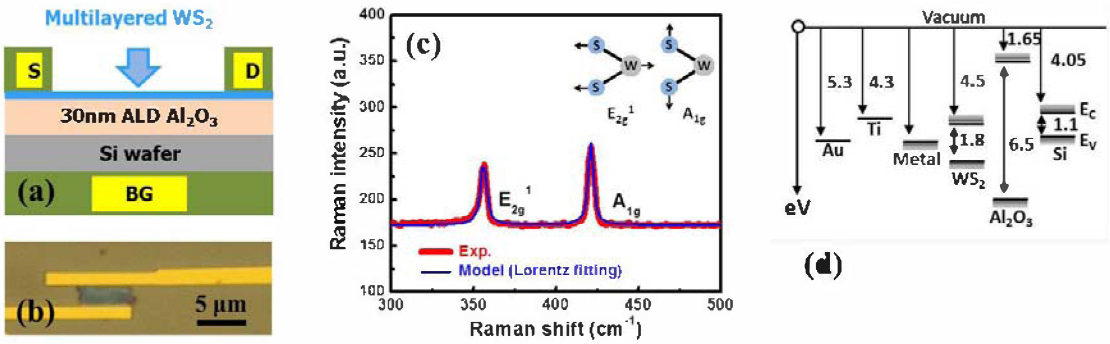

FIG. 1. (a) Schematic cross-section, (b) optical image of the WS_2 transistor with Ti/Au contacts. (c) Raman spectra (λ = 488 nm) of the multilayered WS_2. The inset shows the two primary vibrational modes of WS_2 leading to the two peaks in the Raman spectrum. (d) Work function, electron affinities, and bandgaps of each element indicating the formation of a Schottky barrier contact between metal and WS_2.

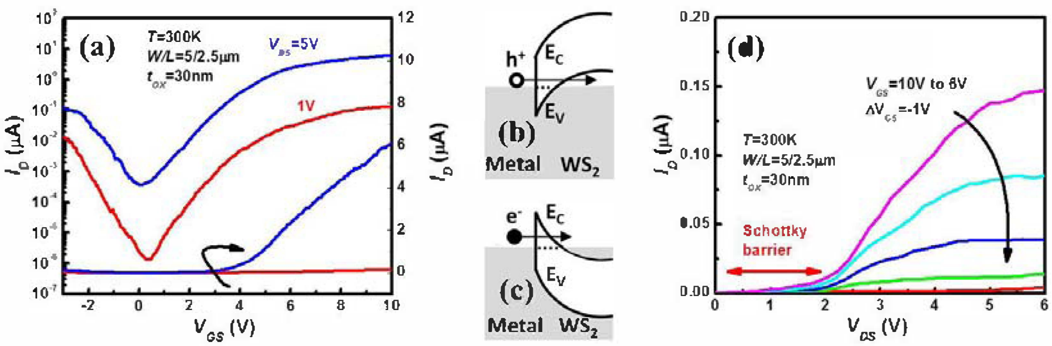

FIG. 2. (a) Drain current I_D *vs*. gate-to-source voltage V_{GS} showing ~$10^5\times$ on/off current ratio and ambipolar behavior. Schematic image of (b) accumulation of holes (*p*-type conductivity) at negative V_{GS} and (c) accumulation of electrons (*n*-type conductivity) at positive V_{GS}. (d) Common-source transistor characteristics, I_D *vs.* V_{DS} indicating the presence of Schottky barrier limited-current injection and current saturation.

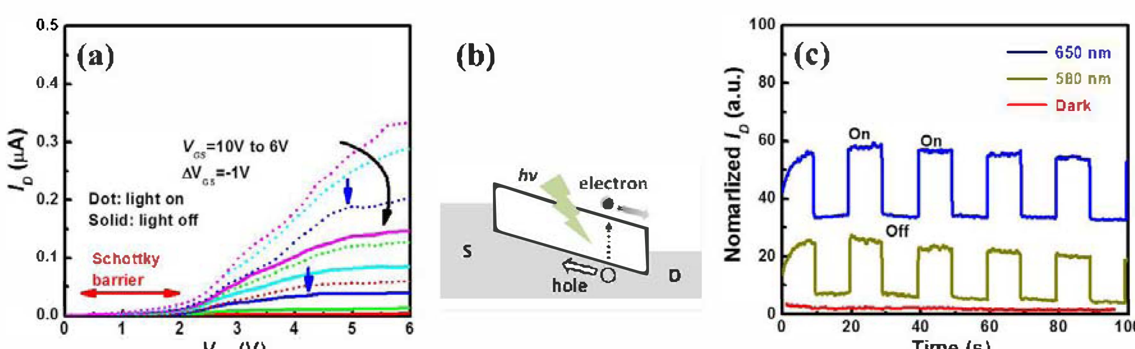

FIG. 3. (a) Dependence of WS_2 common-source characteristics on illumination. (b) Schematic representation of electron-hole pair generation by photon absorption, (c) The temporal photocurrent response of 2D WS_2 device at V_{DS} = 5 V and V_{GS} = 0 V at two wavelengths.