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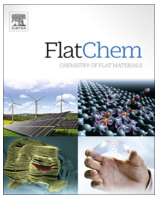

Low-voltage complementary inverters based on ion gel-gated ReS_2 and BP transistors

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ABSTRACT

We demonstrated the preparation of low-voltage complementary inverters based on transistors made of ion gel-gated 2D materials. Mechanically-exfoliated ReS_2 was utilized as an *n*-type semiconductor. The ultrahigh capacitance (6 $\mu F/cm^2$) and long-range polarizability of the ion gel gate dielectric layer provided low-voltage operation below 2 V and allowed a coplanar-gate configuration of the transistors. The ion gel-gated ReS_2 transistors exhibited excellent device performance including an electron mobility of 6.7 cm^2/Vs and an on-off current ratio of $\sim 10^4$. Both the charge-transport mechanism and the contact properties of the device were investigated systematically by measuring the temperature-dependent electrical properties. Mechanically-exfoliated black phosphorous (BP) or WSe_2 was employed as the *p*-type counterpart semiconductors to fabricate the complementary inverter. The resulting 2D complementary inverter exhibited low-voltage operation below 2 V with clear signal inversion. The proposed low-voltage ion gel-gated complementary inverter based on 2D materials opens up new opportunities for realizing future electronics based on 2D materials.

Introduction

Over the past decade, atomically-thin, two-dimensional (2D) layered materials have attracted great attention for their potential use in solid-state device technologies as alternatives to silicon [1–10]. In particular, transition metal dichalcogenides (TMDCs) with the chemical formula MX_2, where M is a transition metal (Mo, W, or Re) and X is a chalcogen (S, Se, or Te), have emerged to open an era of 'post-graphene' 2D electronics; these materials are attractive due to their finite band gap energies ranging from 0.5 to 4 eV [11–18]. Therefore, much research, including both theoretical and experimental exploration, has been conducted on a variety of TMDCs. Recently, a new TMDC material composed of rhenium disulfide (ReS_2) was discovered [19,20]. Due to its anisotropic carrier transport and photonic response that vary with the axial direction, ReS_2 offers exciting opportunities for applications in various electronic and optoelectronic devices [19–25]. Notably, its bulk material behaves electronically and vibrationally like a few decoupled monolayers; this behavior is due to the lack of interlayer registry and weak interlayer coupling, arising from Peierls distortion of the 1T structure [19,23,26]. Thus, ReS_2 possesses a direct band gap of ~1.5 eV, regardless of the layer number. Compared with other TMDCs such as MoS_2, WS_2, and WSe_2, which have layer number-dependent band gap energies (1.2 and 1.8 eV for single-layer and bulk MoS_2, respectively) [18], precise control of the layer thickness is not required to achieve uniform and reliable transistor performance in a large-area array.

Complementary metal-oxide-semiconductor (CMOS) circuits are desirable because their *n*-channel and *p*-channel transistors function in concert, their power dissipation requirements are low, and their noise tolerance margin is high [27,28]; these circuits also have high operating speeds and excellent robustness [29]. However, despite these advantages, many research groups have instead opted to fabricate depletion-load inverters using single unipolar 2D flakes due to the simpler fabrication procedure [30–33]. Although a few complementary inverters have been demonstrated by combining *n*-type MoS_2 with *p*-type $MoTe_2$ or WSe_2 [34,35], complementary inverters with *n*-type ReS_2 have never been reported. From a practical perspective, the operational voltage window of an inverter should be lowered by selecting an appropriate gate dielectric layer.

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In this manuscript, we demonstrated a low-voltage complementary inverter based on transistors made of an ion gel-gated 2D material. Mechanically-exfoliated ReS_2 and black phosphorous (or WSe_2) were utilized as *n*-type and *p*-type semiconductors, respectively. The ultrahigh capacitance of the ion gel gate dielectric layer ($6\ \mu F/cm^2$) provided low-voltage operation of both the transistor and inverter. In addition, the long-range polarizability of the ion gel enabled the gate electrode to be positioned such that it was coplanar with the transistor channel. The ion gel-gated 2D transistors exhibited good device performance including low-voltage operation with a high transconductance, carrier mobility, and on-off current ratio. Moreover, temperature-dependent transport measurements were carried out to investigate both the charge-transport mechanism and the contact properties of the ion gel-gated 2D transistors. The resulting complementary inverter based on an *n*-type ReS_2 transistor with a *p*-type BP (or WSe_2) transistor exhibited low-voltage operation below 2 V with clear signal inversion. The proposed low-voltage 2D complementary inverter opens up new opportunities for future electronics based on 2D materials.

Experimental section

First, ReS_2, BP, and WSe_2 flakes were exfoliated mechanically from bulk crystals (SPI Supplies, Inc.) using Scotch tape [5]. These flakes were transferred directly onto Si/SiO_2 substrates in a glove box. Raman spectra of the flakes were obtained using an NTMDT AFM-Raman spectroscope with a 532-nm-wavelength laser. Atomic force microscopy (Seiko Instruments) was used to measure the thicknesses of the flakes. Conventional electron-beam lithography was utilized to form the Cr/Au (3/40 nm) metallic contacts, including the source, drain, and coplanar gate electrodes. Finally, the ion gel gate dielectric layers were patterned across the channel of the *p*-type (or *n*-type) transistor and coplanar gate electrodes. The UV-patternable ion gel was composed of a 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide [EMIM:TFSI] ionic liquid, poly(ethylene glycol) diacrylate (PEGDA) monomer, and 2-hydroxy-2-methylpropiophenone (HOMPP) photoinitiator at a weight ratio of 22:2:1. The channel region was exposed to UV light, and the unexposed part was rinsed with deionized water. Electrical characterization was carried out under dark and vacuum conditions ($\sim 10^{-4}$ Torr) with a Keithley 4200-SCS instrument.

Results and discussion

Fig. 1a illustrates the fabrication process of the complementary inverter consisting of *n*-type ReS_2 and *p*-type BP transistors with ion gel gate dielectrics. First, ReS_2 and BP flake films were mechanically exfoliated onto a Si wafer from ReS_2 and BP bulk crystals, respectively, using Scotch tape. The mechanical exfoliation of flakes was conducted in a glove box to minimize unwanted damage induced by oxygen or water molecules. Metallic contacts (Cr/Au = 3/40 nm) were fabricated to form the source, drain, and coplanar gate electrodes by a conventional e-beam lithography technique. Finally, an ion gel gate dielectric layer consisting of a 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ([EMIM][TFSI]) ionic liquid, poly(ethylene glycol) diacrylate (PEG-DA) monomer, and 2-hydroxy-2-methylpropiophenone (HOMPP) initiator with a weight ratio of 88:8:4 was patterned across the ReS_2 and BP channels of both transistors and coplanar gate electrodes [36,37]. The equivalent circuit diagram of the resulting complementary inverter is shown in Fig. 1b. The mechanically-exfoliated ReS_2 and BP flakes were characterized by optical microscopy (OM), atomic force microscopy (AFM), and Raman spectroscopy. Fig. 1c shows the OM image of the ReS_2 and BP flakes with Cr/Au contacts. The thickness of the ReS_2 layer was confirmed by AFM; this was approximately 3 nm, which corresponded to four layers of ReS_2 [38,39]. The thickness of the BP film was around 10 nm, corresponding to 17 layers [40–42]. The Raman spectrum of ReS_2 in the upper panel of Fig. 1d exhibited three main characteristic peaks located at 163, 220, and 340 cm^{-1}; these were attributed to the in-plane E_{2g}, mostly-out-of-plane A_{1g}-like, and mostly-in-plane E_{1g}-like vibrational Raman modes, respectively [38]. The peak positions of our ReS_2 layer were consistent with those of a

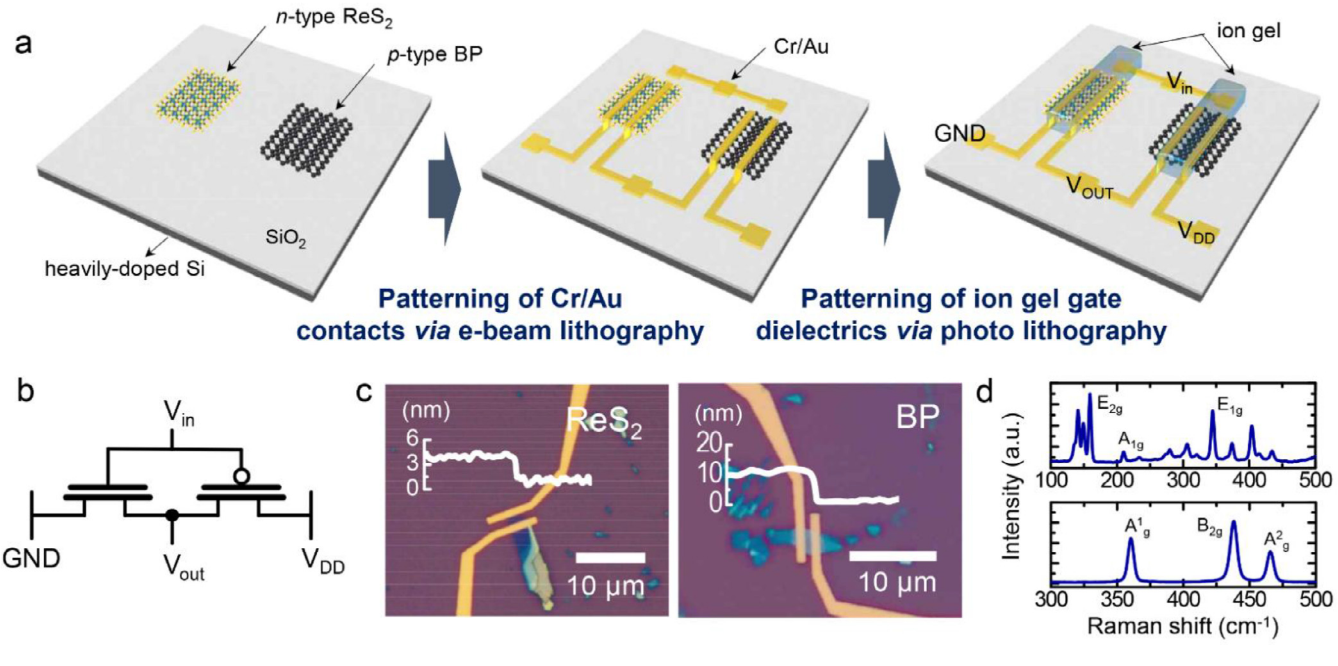

Fig. 1. (a) Schematic of the fabrication procedure of the complementary inverter based on *n*-type ReS_2 and *p*-type BP transistors with ion gel gate dielectrics. (b) Equivalent circuit of the complementary inverter. (c) Optical microscopy images of both ReS_2 and BP transistors. The inset shows the height profiles of mechanically-exfoliated ReS_2 and BP flakes, as determined by AFM. (d) Raman spectra of ReS_2 and BP flakes.

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