AIP Applied Physics Letters

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Citation: Applied Physics Letters **104**, 022110 (2014); doi: 10.1063/1.4862328
View online: http://dx.doi.org/10.1063/1.4862328
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/104/2?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **104**, 022110 (2014)

Nanobridge gate-all-around phototransistors for electro-optical OR gate circuit and frequency doubler applications

Jin Yong Oh and M. Saif Islam[a)]
Department of Electrical and Computer Engineering and Center for Nano and Micro Manufacturing, University of California-Davis, One Shield Avenue, Davis, California 95616, USA

(Received 16 December 2013; accepted 3 January 2014; published online 16 January 2014)

We fabricated photosensitive silicon-nanobridge 3-D field-effect-transistors and demonstrated their analog and digital applications. The channels of the transistors were implemented by nanowires, grown and bridged between pairs of silicon electrodes using the vapor-liquid-solid technique. Whilst characteristics of the nanowire transistor such as the inverse sub-threshold slopes, the on-current, and the threshold voltage remained nearly unaffected by illumination, magnitude of the off-current was significantly increased by up to three orders of magnitude with increasing intensity. Such off-current modulation enabled by illumination offers opportunities for applications such as electro-optical OR gate circuit elements and frequency doublers. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4862328]

Phototransistors are active devices wherein current is modulated by external light. They have rather similar or same structures to those of the conventional field-effect-transistors (FETs) and their channel respond sensitively to illumination. Depending on the energy bandgaps of the channel materials, phototransistors can detect a wide range of spectrum spanning from UV to IR with high response and gains.[1,2] What makes them more attractive is that in addition to the external gates enabled by light, when optically transparent gate electrodes are implemented on their channel, phototransistors can exploit both electrical and optical switching capability.[3,4] Such characteristics are useful in designing various kinds of electro-optical devices for sensing, detection, switching, and logic operations.

Phototransistors have been created by diverse semiconducting materials such as Si,[2] Ge,[5] SiGe,[6] GaAs,[7] a-IGZO,[8] and organic films.[3] In the recent past, semiconductor nanowires have attracted attention for realizing highly sensitive phototransistors because, compared to their bulk counterparts, their large surface-to-volume ratios and intrinsically small dimensions contribute to enhanced photosensitivity.[9–11] Furthermore, when they are gated by bottom electrodes underneath the gate dielectric, the transistors can exploit the nanowire channel's superior sensitivities to gases, chemicals, and bio-molecules, with which we can design multifunctional devices. For instance, III–V and CuO nanowire transistors exemplified gas sensing as well as electrical switching operations.[12,13]

For practical applications, however, nanowires should be integrated in a large array for realizing identical characteristics of unit devices, which can hardly be realized via a "pick and place" approach. Alternatively, nanowire bridges (nanobridges) enable facile integration of crystallographically aligned nanowires on pre-patterned semiconductor electrodes.[14,15] These nanobridges can be used as channels of FETs,[16] photodetectors,[17] or sensors.[18] In the present work, we demonstrated and characterized photosensitive nanobridge gate-all-around (GAA)-FETs. Using their off-currents that increase selectively with illumination, we also presented multifunctional digital and analog devices such as an electro-optical input OR gate circuit and a frequency doubler.

Nanobridge GAA-FETs were fabricated using suspended *p*-type, $\langle 111 \rangle$ oriented silicon (Si) nanowires, which were integrated between pairs of *p*-type Si electrodes ($>1\times10^{19}\,\mathrm{cm}^{-3}$) on a Si-on-insulator (SOI). The doping level of the nanowires was estimated to be $\sim5\times10^{16}\,\mathrm{cm}^{-3}$. The nanowires were synthesized using vapor-liquid-solid technique in a cold-wall chemical-vapor-deposition tool (First Nano® Easy Tube 3000). Effective lengths of the nanobridges and the gate were determined by the space gaps (4–11 μm) of the electrode pairs where nanobridges were formed and the thickness of the nanowires was about 150–200 nm. Detailed experimental procedures have been presented in our previous work.[19] For fabrication of the GAA-FETs, the nanobridges were treated with a gold etchant and then oxidized to grow 10 nm thick SiO_2, followed by the deposition of conductive amorphous Si for forming surrounding gates. Pt ohmic contact pads were then deposited on source/drain Si electrodes. A 2-D schematic diagram and a micrograph of the nanobridge GAA-FET are shown in Fig. 1(a). Our photocurrent measurement setup was composed of an Agilent 4156C and an optical microscope where white light of a tungsten halogen lamp was focused onto the devices through a 10× or 20× objective lens. Illumination power was measured with an optical power meter, Thorlabs PM100.

In the dark, experimental measurement of source current (I_S)-gate voltage (V_{GS}) collected from a nanowire GAA-FET exhibited typical *p*-type transfer characteristics (Fig. 1(b)). For $V_{GS} > -2$ V, off-current increases as V_{GS} and drain voltages (V_{DS}) increase, which is presumably due to gate-induced-drain-leakage (GIDL).[20] In sharp contrast, off-current drastically increases with white light illumination. As shown in the inset of Fig. 1(b), for illumination intensity of 8 mW/cm^2, ratios of off-current with illumination (I_L) to that in the dark (I_D) increase by more than two orders of

a)Electronic mail: sislam@ucdavis.edu

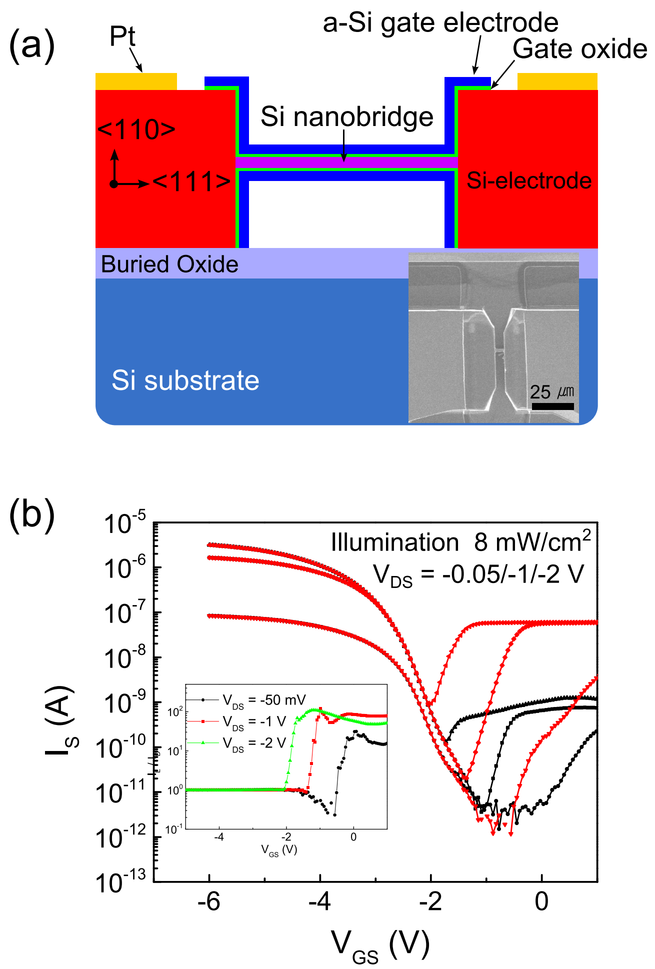

FIG. 1. (a) A 2-D schematic diagram of a Si nanobridge GAA-phototransistor and its SEM micrograph shown in the inset. Here, the length and thickness of the nanobridges were 5 μm and 180 nm, respectively. (b) Measured current-voltage (I_S-V_{GS}) characteristics collected from the GAA-phototransistor with and without illumination of 8 mW/cm^2. Ratios of off-current with illumination (I_L) to that in dark (I_D) are shown in the inset.

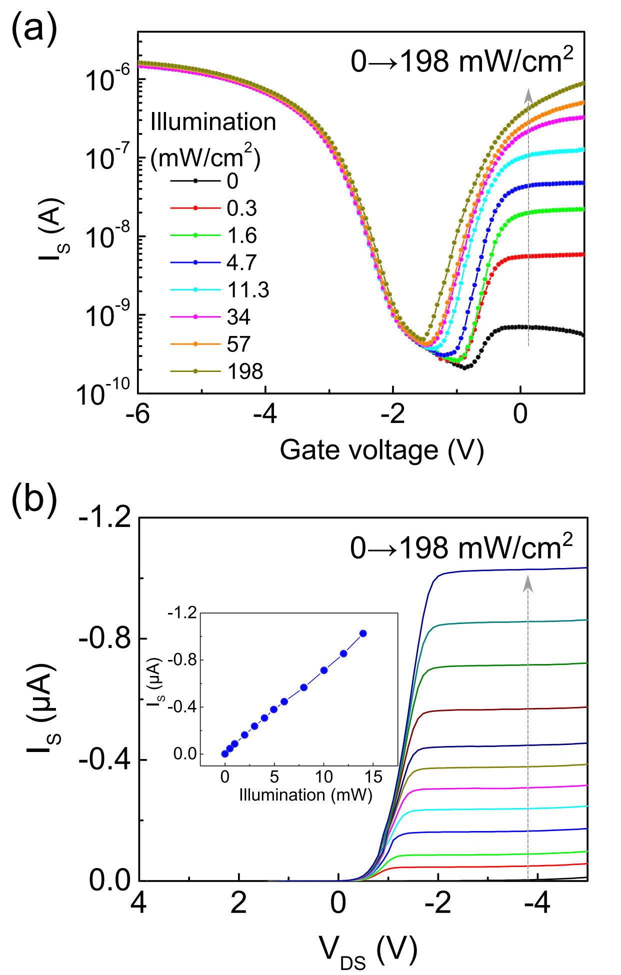

FIG. 2. (a) Measured I_S-V_{GS} curves with illumination of different intensities from 0-198 mW/cm^2. (b) Output characteristics (I_S-V_{DS}) with photo-gate. The inset in (b) shows a linear increase of photocurrent collected for $V_{DS} = -2.5$ V with increasing illumination intensities. Note that while the off-current in (a) drastically increases with illumination, the on-current increases by 10%, and subthreshold slopes and threshold voltages remain almost unaffected by illumination.

magnitude. Increased off-current with illumination can be attributed to photo-generated electron-hole pairs that flow toward the junction of nanobridges-electrodes and subsequently enhance GIDL. Off-current with illumination (I_L), however, saturates as V_{GS} rises above -1.5 V and -0.5 V for $V_{DS} = -2$ V and -1 V, respectively, because voltage drops get considerably large along the depletion region in the nanowire channel as well as in the junction.

Off-current measured from the nanobridge GAA-FET significantly increased to be comparable to on-current when illumination intensity rises from 0 to 198 mW/cm^2 as shown in Fig. 2(a). The magnitude of off-current for 198 mW/cm^2 of illumination became comparable to on-current, rendering I_S-V_{GS} almost ambipolar. Meanwhile, in the same measurement condition, on-current in the triode and saturation regions increases only about 10%. Also, other parameters of the GAA-FET, such as subthreshold slopes and threshold voltages, remained almost unchanged. This result suggests that the nanobridge GAA-FET can expand its realm from an electrical device to an electro-optical one and therefore enable novel device applications, which will be described below.

Another promising characteristic of our nanobridge GAA-FET is a phototransistor behavior. As exhibited in Fig. 2(b), I_D-V_{DS} curves resemble typical output characteristics of FETs with varying gate voltages. Drain currents increase with drain voltages but start to saturate between $V_{DS} = -1$ and -2 V. They were also modulated by illumination that serves as a photo-gate. As plotted in the inset of Fig. 2(b), drain current in the pinch-off region increases linearly with the illumination intensity. Despite high linearity, the photosensitivity calculated from the curve was about 7×10^{-5} A/W, which is quite small compared to those of other phototransistors.[21,22] However, it can be further improved through optimizing the series resistance of the device and employing transparent gate electrode.

Illumination-enabled modulation of the off-current with stable electro-switching properties of the nanobridge phototransistor demonstrates the potential for realizing multifunctional devices. We designed, for instance, an electro-optical OR gate circuit,[3] as illustrated in Fig. 3(a). Its output voltages are driven by two inputs, gate voltages (A_{IN}) and illumination (B_{IN}). As shown in Fig. 3(b), when square-pulse voltage signals were introduced to A_{IN}, the output voltages were accordingly varied. Likewise, for two second pulsed

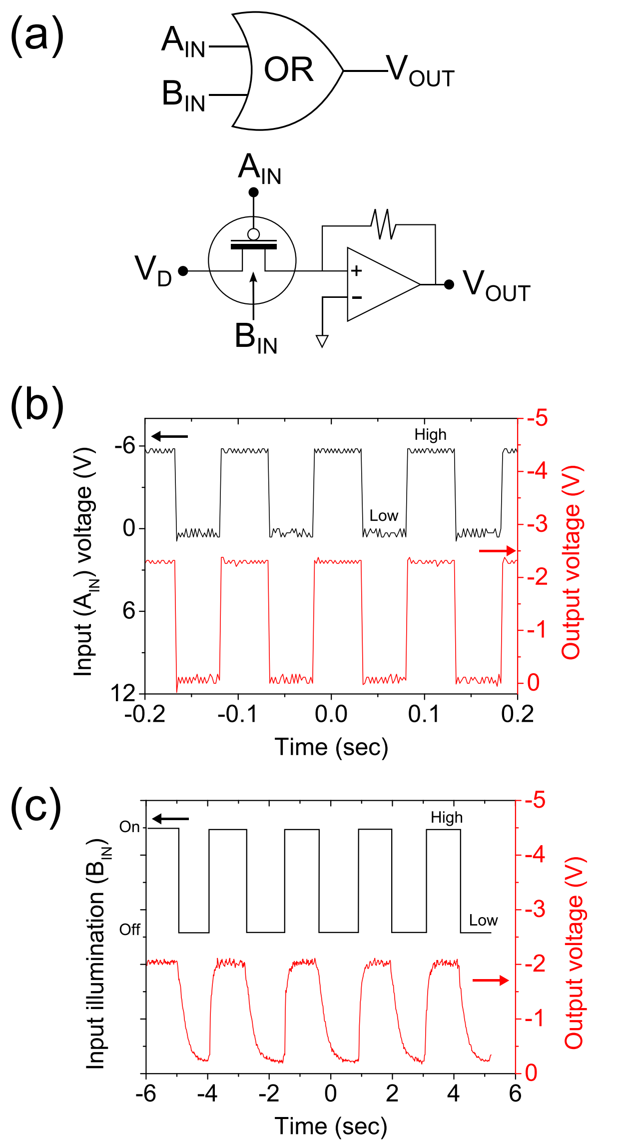

FIG. 3. (a) Symbolic representation of an electro-optical OR gate (upper) and its circuit diagram (lower). (b) Ouput voltages with an electrical input (A_{IN}) (upper) in dark and optical input (B_{IN}) (lower) with low $A_{IN.}$ It should be noted that a discernable delay in the fall-time of the output pulses is caused by the latent light from the tungsten-halogen bulb.

illumination, output pulses succeed the illumination states in the OR gate circuit (Fig. 3(c)).

Since noticeable ambipolarity appears with high intensity of illumination, we can take advantage of this characteristic to design a frequency doubler, which can be selectively turned on and off by existence of illumination. Employing the OR gate circuit, we applied sinusoidal signal (100 Hz) at the gate with $V_{DS} = -1.5$ V. In the dark, as shown in Fig. 4(a), the circuit shows output responses with the same frequency to that of the gate voltage. With 190 mW/cm^2 of illumination, on the other hand, the circuit resulted in an output with the doubled frequency of an input. Frequency spectra (not shown here) of both output signals with and without illumination, calculated using fast-Fourier-transform, present two distinct peak-frequencies of 100 and 200 Hz. Although this frequency doubler could operate limitedly in a frequency of less than 600 Hz due to a considerable RC delay and in relatively high illumination intensity, further optimization

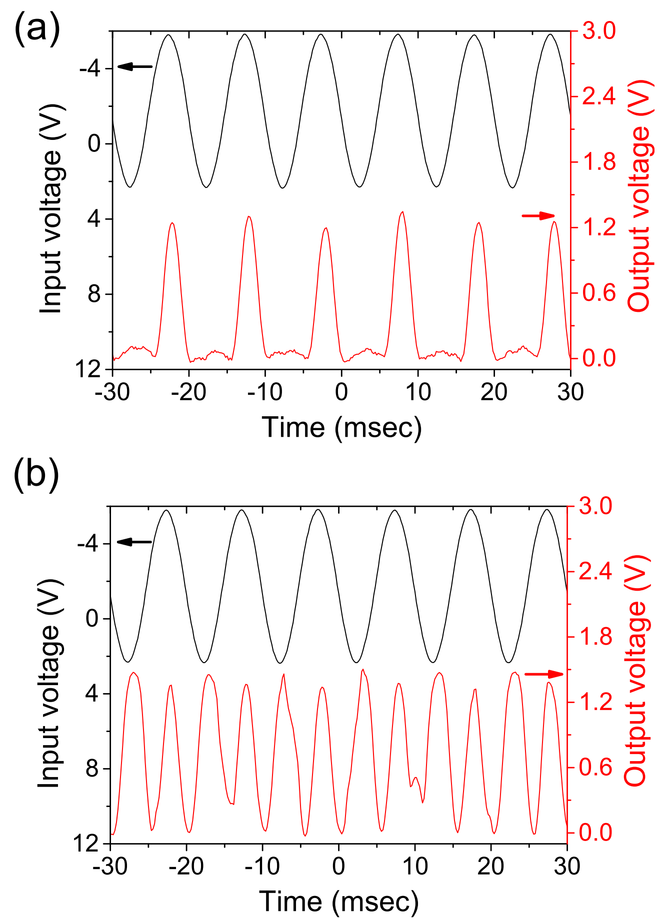

FIG. 4. Illumination-regulating frequency doubling characteristics of the circuit illustrated in Figure 3. Input and output voltages measured (a) without illumination and (b) with illumination intensity of 190 mW/cm^2.

for reducing magnitudes of series resistance, capacitance of the nanobridge GAA-FETs and enhancing the photosensitivity of off-current would address the narrow operational windows of input frequencies and illumination intensities.

In summary, we demonstrated photosensitive 3-D Si nanobridge GAA-FETs integrated in an array using a high-throughput fabrication technique. Off-current of the nanobridge GAA-FET increases by three orders of magnitude with wide-spectral illumination. The device also showed phototransistors characteristics in which output current was linearly modulated with the incident illumination. Photosensitive off-current of the GAA-FET allowed for the demonstration of digital and analog applications, such as an electro-optical OR gate circuit and an illumination-enabled frequency doubler. When they are associated with more photosensitive compound semiconductor nanowires such as ZnO[1] and InP,[2,3] the nanobridge GAA-FETs can be exploited for realizing multifunctional devices including optoelectronic transceivers as well as sensors.

This work was partially supported by NSF Grant No. CMMI-0547113 and CMMI-1235592.

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