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Ran Yu,[a] Isabelle Ferain, Nima Dehdashti Akhavan, Pedram Razavi, Ray Duffy, and Jean-Pierre Colinge
Tyndall National Institute, University College Cork, Lee Maltings, Prospect Row, Cork, Ireland

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A diode has been realised using a silicon junctionless (JL) transistor. The device contains neither PN junction nor Schottky junction. The device is measured at different temperatures. The characteristics of the JL diode are essentially identical to those of a regular PN junction diode. The JL diode has an on/off current ratio of 10^8, an ideality factor of 1.09, and a reverse leakage current of 1×10^{-14} A at room temperature. The mechanism of the leakage current is discussed using the activation energy (E_A). The turn-on voltage of the device can be tuned by JL transistor threshold voltage. © *2011 American Institute of Physics*. [doi:10.1063/1.3608150]

The junctionless (JL) metal-oxide-semiconductor field-effect transistor (MOSFET) has been recently introduced and is a promising candidate for end-of-roadmap complementary metal-oxide-semiconductor (CMOS) circuit fabrication.[1,2] In a JL transistor, the doping concentration is constant through the source, and channel and drain are doped. Typical doping concentration is in the range of few 10^{19} cm^{-3}. The device can be turned off by the gate through inducing full depletion of the carriers in the highly doped channel region. A positive threshold voltage can be obtained for n-channel MOSFET devices by using a gate material with a large workfunction, such as P+ polycrystalline silicon or platinum. The threshold voltage can be further tuned by modifying the printed width of the nanowire.[3,4] The electrical properties of JL transistor have been reported in several publications.[5–9] However, the operation of the device in the diode configuration has not been reported yet. The diode configuration setup is commonly used in circuit designs.[10]

The JL diode is obtained by shorting the gate and drain electrodes of a JL transistor [Fig. 1(a)]. The JL transistor used here has a gate length of 1 μm and a cross section of approximately 10 nm × 10 nm. The n-type JL transistor has a uniform doping concentration of 1×10^{19} cm^{-3} in the source, drain, and channel regions [Fig. 1(b)]. The gate oxide thickness is 7 nm. The performance of the diode is measured by Cascade thermal probe station and Agilent B1500 semiconductor parameter analyzer.

Figure 2 shows the experimental $I(V_A)$ characteristics of the JL diode in the dark [Fig. 2(a)] and under microscope light illumination [Fig. 2(b)], where V_A is the applied voltage on the JL diode. In Fig. 2(a), the dark current of the JL diode is lower than 10^{-14} A and an on/off current ratio of 10^8 is observed at 20 °C. When the temperature is increased, the dark current increases and is attributed to the increase of intrinsic carrier concentration but remains low compared to the dark current of silicon on insulator diodes based on MOSFETs with junctions.[10] When under illumination, in Fig. 2(b), the current under reverse bias increases due to the photogeneration of electron-hole pairs. Under forward bias, the slope of the $\log(I(V_A))$ curves decreases as temperature is increased, which is commonly observed in regular PN junction diodes.[11] In our device, this is caused by the increase of subthreshold slope of the JL transistor with temperature.

The electrical characteristics of the JL diode are substantially similar to those of a regular PN junction diode. However, the physics involved is quite different. In a PN junction, the forward current results from the recombination of electrons injected in the P-type region and the recombination of holes injected in the N-type region. In the JL diode, the current is formed by the drift/diffusion of majority carriers (electrons) in the channel region, where the electron concentration varies exponentially with the gate bias. In a classical PN junction diode, generation/recombination mechanisms in the transition region are the main source of reverse current; they also degrade (decrease) the slope of the $\log(I(V_A))$ curve in forward bias operation.[12] The total current in the diode can be expressed by a single relationship that encompasses both diffusion current and generation/recombination:

$$I = I_S\left[\exp\left(\frac{qV_A}{nkT}\right) - 1\right], \tag{1}$$

where I_s is the reverse saturation current, n is the ideality factor, q is the charge of electron, k is Boltzmann's constant,

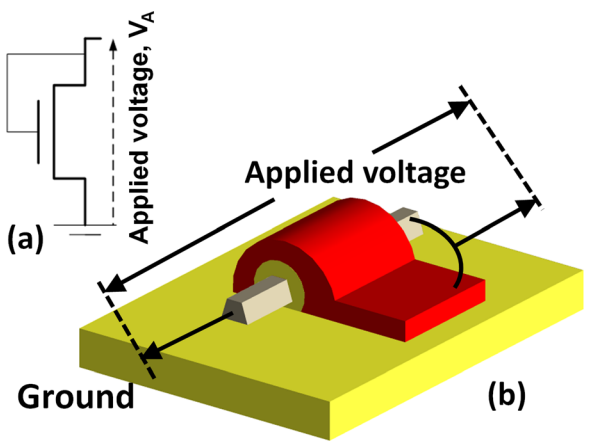

FIG. 1. (Color online) (a) Schematic representation for the JL transistor in diode configuration (circuit symbol). (b) Schematic diagram of the structure of a JL diode.

[a]Electronic mail: ran.yu@tyndall.ie.

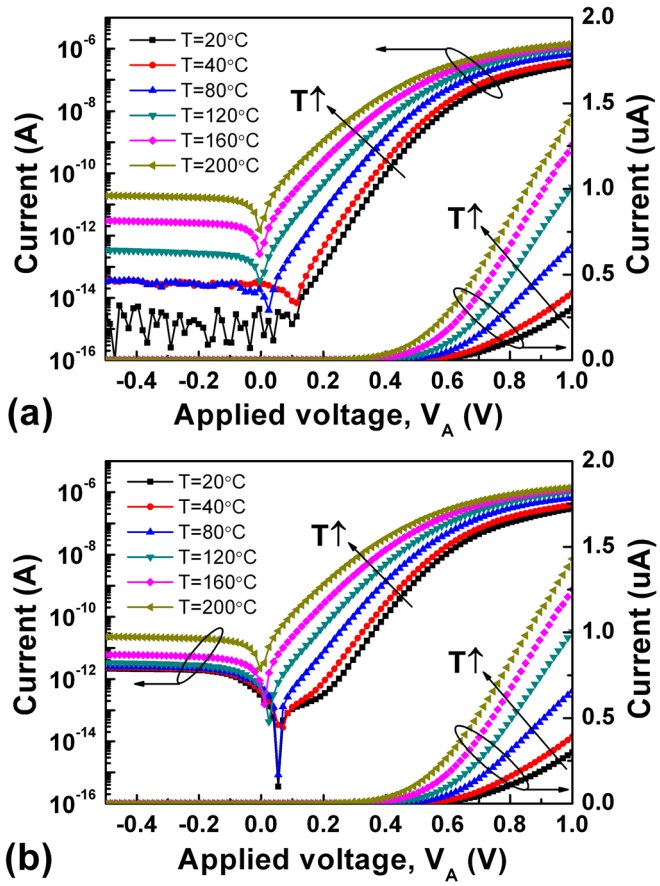

FIG. 2. (Color online) $I(V_A)$ characteristics of the JL diode in linear and log scale (a) in the dark and (b) under illumination at temperatures ranging from 20 °C to 200 °C.

and T is the temperature in kelvin (K). The value of the ideality factor varies between 1 and 2. It is equal to 1 in the case of a pure diffusion current and to 2 in the case where the current is entirely dominated by recombination/generation mechanisms in the transition region. In the JL diode, these generation/recombination mechanisms take place in the fully depleted channel region instead. We extracted the ideality factor of JL diodes from their $I(V_A)$ curves, using the following expression derived from Eq. (1) under forward biasing conditions:

$$n = \frac{dV_A}{d(\ln(I))} \times \frac{q}{kT}. \tag{2}$$

Figure 3(a) shows the values of n of the JL diode at temperature ranging from 20 °C to 200 °C. An ideality factor close to 1 ($n = 1.1$) is observed for all temperatures. For a decade change in current, ideally the V_A varies by the factor $\Delta V_A = ln10kT/q$. ΔV_A is linearly increased as temperature arises. The measured $\Delta V_A/dec$ values match the theoretical calculation. $\Delta V_A/dec$ values derive from having a subthreshold slope close to $\frac{kT}{q}\ln(10)$ measured in JL transistors over the same range of temperatures and have neglectable degradation when using diode configuration.[7,13]

In CMOS technology, the drain and gate connected transistors present, as a major drawback, high leakage current. However, JL diodes show a significantly reduced leakage current. As leakage current due to band to band tunneling (BBT) and trap-assisted tunneling has strong lateral voltage

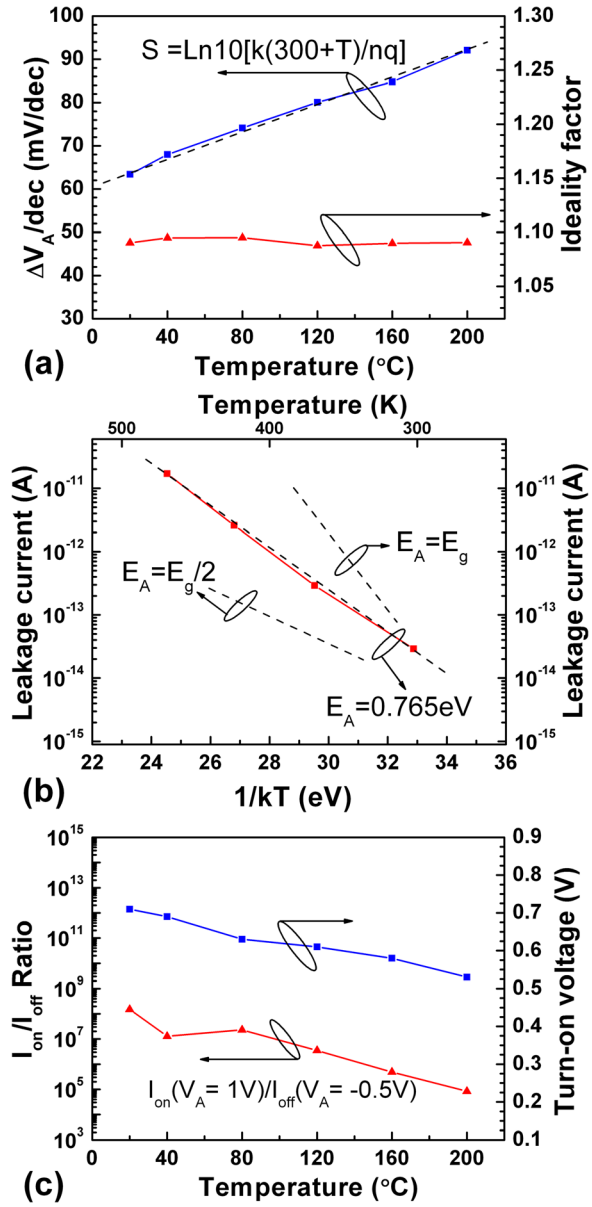

FIG. 3. (Color online) (a) V_A variation for a decade change in current and ideality factor at temperatures ranging from 20 °C to 200 °C. (b) Arrhenius plot of reverse leakage current of the JL diode. (c) On/off current ratio and turn-on voltage of the JL diode at temperatures ranging from 20 °C to 200 °C.

dependence and activation energy (E_A) close to 0 eV for BBT, which has not been observed in our measurements.[14] We consider two components of the off-state leakage current of JL diodes: current due to thermal generation in the depleted body film ($I_{gen,dep}$) and current due to diffusion at the edge of neutral body just outside the channel-drain junction (I_{diff}) (Ref. 15):

$$I_{Leakage} = I_{gen,dep} + I_{diff} \tag{3}$$

For the first component, electron-holes pairs are generated in the depleted nanowire and it is temperature-dependent. The generated electrons are swept to the drain and the generated holes are attracted to the source. The current is due to the thermal generation inside the depleted region and given by[15]

$$Igen, dep = \frac{qn_i}{\tau_g} V \tag{4}$$

where n_i is the intrinsic electron concentration, τ_g is the effective generation lifetime inside the depletion region, and V is the volume of the depletion region. The temperature dependence behaviour of the leakage current is related to the temperature dependence of n_i which is proportional to $\exp(-E_g/2kT)$, where E_g is the band gap of silicon. Thus $I_{gen,dep}$ is proportional to $\exp(-E_g/2kT)$, and the E_A expected to be 0.56 eV. The second current component is due to diffusion at the edge of neutral body film just outside of the depletion region in the channel-drain junction. This current is usually called diffusion current and expressed as[15]

$$I_{diff} = q\sqrt{\frac{D_n}{\tau_n}}\frac{n_i^2}{N_d}\left(\exp\left(\frac{q(\varphi_S - V_D)}{kT}\right) - 1\right)A, \qquad (5)$$

where D_n is the electron diffusion coefficient, τ_n is the electron lifetime inside the depletion region, V_D is the applied voltage at drain, φ_S is the surface potential in the depletion region close to drain, and A is the area of the channel-drain junction. The diffusion current in JL diode is approximately proportional to n_i^2. Thus, I_{diff} is proportional to $\exp(-E_g/kT)$, and E_A expected to be 1.12 eV. Figure 3(b) shows the activation energy extracted from the average of reverse leakage current curves measured in the dark ($V_A = -0.5$ V to -0.1 V). $E_A = 0.765$ eV indicates thar the leakage currents are mainly dominated by thermal generation current in depletion region. The diffusion component of the leakage current makes $E_A > E_g/2$. It is also noted that I_{diff} is also increased by $|\varphi_S - V_D|$ exponentially. As the gate and drain are shorted in the JL diode, drain voltage (V_D) and gate voltage (V_G) are identical. ϕ_S changes slower than V_G,[11] thus $|\phi_S - V_D|$ is increased slightly when $|V_A|$ arises. Thus, I_{diff} increases slightly when larger reverse voltage applied. This is consistent with the results observed in Fig. 2.

Figure 3(c) shows that the turn-on voltage of the JL diode decreases from 0.73 V to 0.51 V as the temperature is increased from 20 °C to 200 °C. This shift is related to the shift in threshold voltage of the JL nanowire transistor with temperature.[5] Indeed, unlike in regular PN junction diodes, the turn-on voltage of JL diodes is not determined by the band gap but by the threshold voltage of the JL transistor.[16] Lower turn-on voltage can readily be achieved by tuning the cross-sectional dimensions of the nanowire or the gate material. The on and off currents are extracted at $V_A = 1$ V and -0.5 V, respectively. The on/off current ratios degrade with temperature, due to the exponential increase of the leakage currents and smaller current change under forward bias.

In conclusion, we observe that a JL nanowire transistor connected in the diode configuration presents characteristics similar to those of a regular PN junction diode. An ideality factor close to unity is observed in the temperature range 20 °C to 200 °C. Leakage currents due to thermal generation and diffusion is evident as $E_A = 0.765$ eV. The diode turn-on voltage can be tuned by varying the threshold voltage of the junctionless transistor.

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