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A silicon nanowire heater and thermometer

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In the thermal conductivity measurements of thermoelectric materials, heaters and thermometers made of the same semiconducting materials under test, forming a homogeneous system, will significantly simplify fabrication and integration. In this work, we demonstrate a high-performance heater and thermometer made of single silicon nanowires (SiNWs). The SiNWs are patterned out of a silicon-on-insulator wafer by CMOS-compatible fabrication processes. The electronic properties of the nanowires are characterized by four-probe and low temperature Hall effect measurements. The *I-V* curves of the nanowires are linear at small voltage bias. The temperature dependence of the nanowire resistance allows the nanowire to be used as a highly sensitive thermometer. At high voltage bias, the *I-V* curves of the nanowire become nonlinear due to the effect of Joule heating. The temperature of the nanowire heater can be accurately monitored by the nanowire itself as a thermometer. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4985632]

In search of high-performance thermoelectric materials and devices, the accurate measurement of thermal conductivity is the key.[1–3] The widely used method for thermal conductivity measurements is to employ micro metal coils as the heater and thermometer.[4–10] The thermal contact resistance between metal coils and the thermoelectric materials is difficult to quantify, which may lead to inaccurate or even artificial findings.[6,7] If the heater and thermometer are made of the semiconducting thermoelectric material under test, then the potential contact resistance will be minimized.[11] What is more, a system made of homogeneous materials will significantly simplify fabrication and integration,[12] which may speed up the process of finding new high-performance thermoelectric materials and devices. Here, we demonstrate a heater and thermometer made of a single semiconducting silicon nanowire (SiNW). The SiNW thermometer relies on the thermal activation of dopants to sense the temperature, as a result of which we find that the nanowire thermometer is much more sensitive than the widely used commercial Pt thermometers. The nanowire can also act as a high-frequency heater at high power feed-through due to its nanoscale size. The temperature of the nanowire heater can be accurately monitored by the nanowire itself as a thermometer.

The silicon nanowires (SiNWs) used in this work were fabricated using the CMOS-compatible process on a silicon-on-insulator (SOI) substrate. The SOI wafer has a 200 nm thick device layer on 380 nm thick SiO_2. The device layer was boron doped at an average doping concentration of $\sim 1 \times 10^{18}\,cm^{-3}$ by ion implantation. Electron beam lithography and thermal evaporation were first used to form a metal mask for patterning the device layer into the nanowires and micropads by reactive ion etch. A thin layer of the Au/Ti (200 nm/5 nm) film was deposited on the micropads by photolithography and metallization. Figure 1(a) shows a scanning electron microscopic (SEM) image of a silicon nanowire device. The nanowire is 24 μm long and 0.4 μm in width. The 6 electrodes lying between the anode and cathode were designed for four-probe and Hall effect measurements.

Temperature dependent current measurements were conducted in the dark in a cryostat (ARS DE-202PI). The samples were placed on the cold finger of the cryostat. The temperature of the cold finger (called as background temperature below) was controlled by a temperature controller (Lakeshore 335). The dc voltage bias V_b is supplied between the anode and cathode by a sourcemeter (Keithley 2400) while the current I_d is monitored at the same time. The voltage V_{46} between electrodes 4 and 6 is also monitored by another sourcemeter at the same time in the four-probe measurements. The measured $I_d - V_{46}$ curves of a single Si NW device at different temperatures under small voltage bias are plotted in Fig. 1(b). The four-probe measurements show that ohmic contacts are formed between the nanowire and metal electrodes and that the contact resistance is negligibly small compared to the nanowire resistance (see supplementary material, Fig. S1). Hall effect measurements were conducted in a Physical Property Measurement System (PPMS EverCool-II). The Hall resistance R_H between electrodes 5 and 6 was measured as a function of magnetic field B at different temperatures, as shown in the inset of Fig. 1(c). The hole concentration p at different temperatures was extracted with the following equation:[13]

$$p = \frac{R_H}{Bqd}, \tag{1}$$

where q is the unit charge and d is the thickness of the nanowire. Figure 1(c) shows the measured hole concentration of a SiNW device as a function of temperature, from which the activation energy is extracted to be 0.043 eV, consistent with the boron ionization energy.[14]

As the voltage bias increases, the I_d-V_{46} curve is no longer linear but bent up at higher voltage bias, as shown in Fig. 2(a). This indicates an increase in the conductivity at higher voltage bias. The increase in conductivity is attributed to a higher concentration of holes, which is confirmed by the Hall measurements as shown in Fig. 2(b). A possible reason

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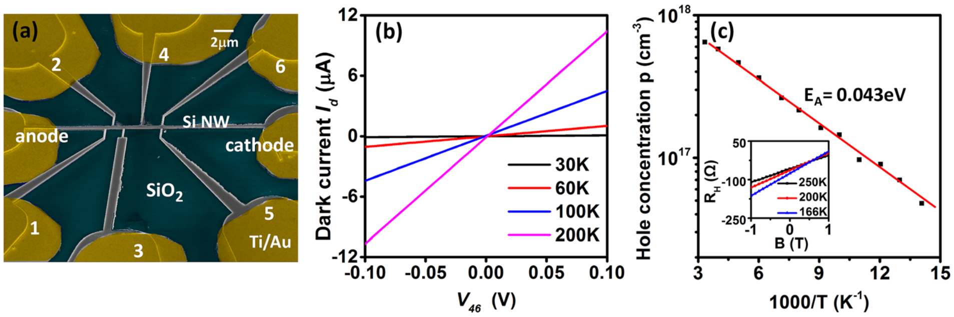

FIG. 1. (a) SEM image with a false color: SiNW device with a width of 400 nm. (b) Four-probe measurements of I_d-V_{46} curves of the silicon nanowire device measured at different temperatures. (c) Hole concentration p as a function of temperature T by Hall measurements. Inset: Hall resistance R_H as a function of magnetic field B at different temperatures.

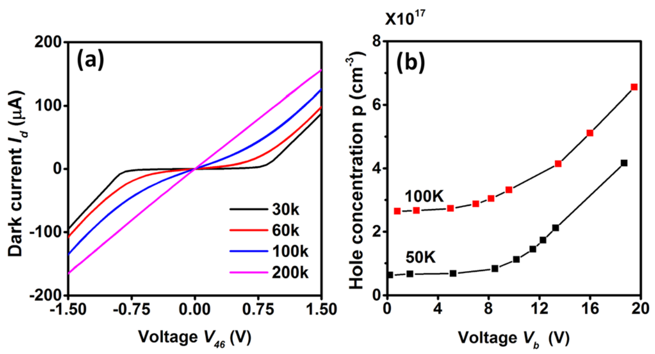

FIG. 2. (a) Four-probe measurements of I_d-V_{46} curves in a large voltage range. (b) Hole concentration p and corresponding temperature T as a function of voltage bias V_b at 50 and 100 K background temperature.

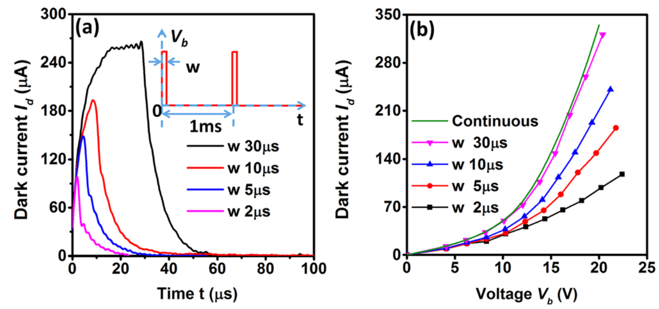

FIG. 3. (a) Transient current response under various voltage pulses. Inset: the voltage pulse applied on the nanowire. (b) I_d-V_b curves under continuous voltage bias and voltage pulse.

for the higher concentration of holes at larger voltage bias is due to Joule heating, since the contact effect has been excluded by the four-probe measurements. At small voltage bias, the Joule heating is negligible. As a result, the I_d-V_{46} curves are linear [Fig. 1(b)]. At high voltage bias, the Joule heating effect cannot be neglected, causing a temperature rise in the nanowire. A higher temperature will increase the boron ionization rate and hence the hole concentration. This increase is less pronounced at high background temperature but clearly visible when the background temperature is lower [Fig. 2(a)], because the rise of temperature will not significantly increase the hole concentration when boron dopants have already been mostly ionized at high temperature.

To further confirm the Joule heating effect, we applied a square wave voltage on the nanowire device and measured the transient current response. The square wave voltage was generated by a function generator (Tektronix AFG3252C) and the transient current response was picked up by an oscilloscope (Rigol DS1102CA). The period of the square wave was fixed at 1 ms and the pulse width w varied from 30 μs down to 2 μs, as shown in the inset of Fig. 3(a) which plots the transient current responses upon the 20 V pulse biases. When the pulse width is 30 μs, the current ramps up rapidly and saturates after 20 μs (much faster than many microsized heaters[15]). As the pulse width decreases, the peak current drops due to the fact that the pulse ON time is not long enough to allow the heat to accumulate, mitigating the rising temperature in the nanowire. Figure 3(b) shows the I_d-V_b curves under continuous and pulse voltage sweep. Clearly, the shorter the pulse width is the more linear the I_d-V_b curve will be. It is evident that the nonlinearity of the I_d-V_b curve is caused by Joule heating.

We have shown above that the nanowire will be rapidly heated up at high voltage bias. Therefore, it can be used as a nanoscale high-frequency (~50 kHz) heat or infrared radiation source. Next, we show how to find the exact temperature of the heated nanowire by using the nanowire itself as a thermometer. As known, the resistance of semiconductors is dominated by the charge carrier concentration. If dopants in semiconductors are not completely ionized, the charge carrier concentration will be strongly dependent on the temperature in the semiconductor. In this case, the semiconductor resistance will be a sensitive function of temperature. This function can be established by sensing the resistance at small voltage bias as we tune the background temperature [Fig. 4(a)]. The temperature of the nanowire is equal to the background temperature because the thermal effect in the SiNW is negligible at small voltage bias. In Fig. 4(a), the resistance R vs temperature T can be fitted with the following equation:

$$R = 1.66\,\mathrm{M\Omega}\exp\left(-\frac{T}{49.85}\right) + 37.99\,\mathrm{M\Omega}\exp\left(-\frac{T}{16.76}\right) + 228.94\,\mathrm{M\Omega}\exp\left(-\frac{T}{8.67}\right) + 0.14\,\mathrm{M\Omega}. \quad (2)$$

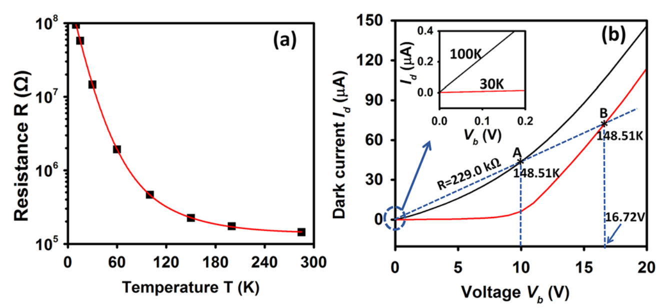

FIG. 4. (a) Resistance R as a function of temperature T under small voltage bias. Black squares: experimental data. Red curve: fitting data. (b) I_d-V_b curve at background temperature 100 K (black) and 30 K (red). Inset: a close-up view of I_d-V_b curves in the bias range of 0 to 0.2 V.

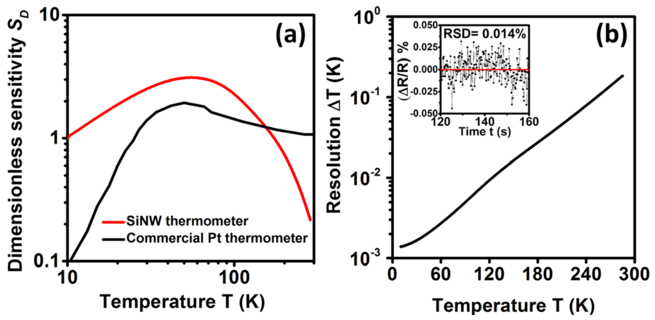

FIG. 5. (a) Dimensionless sensitivity S_D as a function of temperature T. Red curve: SiNW thermometer; black curve: commercial Pt resistance thermometer (100 Ω). Reproduced with permission from C. J. Yeager and S. S. Courts, IEEE Sens. J. 1, 352 (2001). Copyright 2001 IEEE. (b) SiNW thermometer resolution as a function of temperature. Inset: relative standard deviation (RSD) of resistance.

When the nanowire is heated up at high voltage bias, the above equation can be used to find the temperature in the nanowire. For instance, Fig. 4(b) shows the I_d-V_b curves of the silicon nanowire at the background temperature 100 K (back) and 30 K (red). In the case of 100 K, the resistance of the nanowire around 0 V is 441.77 kΩ [inset of Fig. 4(b)]. The resistance is decreased to 229.0 k Ω at a bias of 10 V (Point A, heating power P = 436.6 μW) and the corresponding temperature is 148.51 K according to Fig. 4(a) and Eq. (1). When the background temperature is lowered to 30 K [red line in Fig. 4(b)], the thermal flow to the colder substrate will be larger if we keep the nanowire temperature the same as 148.51 K. As a result, a much larger heating power (1.22 mW) is required to drive the current along the red line to Point B where the nanowire resistance is also 229.0 kΩ (slope of the dashed line from the origin to Points A and B) and the temperature is 148.51 K accordingly.

The dimensionless sensitivity of a thermometer is defined as S_D = (T/R)(dR/dT). The S_D of our SiNW thermometer and a typical commercial Platinum resistance thermometer[16] is plotted together in Fig. 5(a) for comparison. At temperature below 150 K, the SiNW thermometer has a sensitivity higher than the Pt resistance thermometer (more than an order of magnitude higher around 10 K and below). This is because the resistance of the SiNW exponentially increases as temperature decreases due to the incomplete ionization of boron dopants. At higher temperature, the boron dopants are mostly ionized. The rise of temperature has nearly no impact on the hole concentration except that the hole mobility will slightly decrease. Due to this reason, the sensitivity of the SiNW thermometer is lower than that of the Pt resistance thermometer. By introducing some extra deep energy level impurities which may be incompletely ionized even at high temperature, the sensitivity of the SiNW at higher temperature will be significantly enhanced (see supplementary material, Fig. S2). The temperature resolution is also an important parameter for thermometers, which is defined as: $\Delta T = \Delta R/(dR/dT)$. The relative standard deviation of the resistance in our system is 0.014%, as shown in the inset of Fig. 5(b). The temperature resolution is then calculated and plotted in Fig. 5(b), showing that the SiNW thermometer can achieve a resolution as high as ∼1 mK at 10 K. The temperature resolution may even be higher at lower temperature.

In conclusion, we demonstrated a nanoscale high-frequency heater and highly sensitive thermometer based on a single silicon nanowire. Depending on the activation energy of dopants, high-performance nanoscale heaters and thermometers in different temperature ranges can be developed. If properly designed, the nanowire heater and thermometer demonstrated in this work can be applied to the thermal conductivity measurement of nanostructured thermoelectric devices made of the same semiconducting material. It will simplify the fabrication and integration process and speed up the search for high-performance thermoelectric materials and devices.

See supplementary material for contact resistance as a function of temperature and dimensionless sensitivity of sample with deep level impurities.

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