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Supplementary information

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Periodic transparent nanowires in ITO film fabricated via femtosecond laser direct writing

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Section 1: Sheet resistance of the nanostructured ITO film measured by the four-probe method

Four-probe method has been widely used in the semiconductor industry, thin film and surface science. Using four probes instead of two probes to measure the resistivity of the sample can eliminate the influence of probe contact, and has high precision[S1,S2].

The sheet resistance of the ITO film after femtosecond laser direct writing was measured macroscopically by the four-probe measurement, as shown in Fig. S1. Four-probe measurement principle of the thin film model was used to study the sheet resistance of ITO film in the experiments[S3,S4].

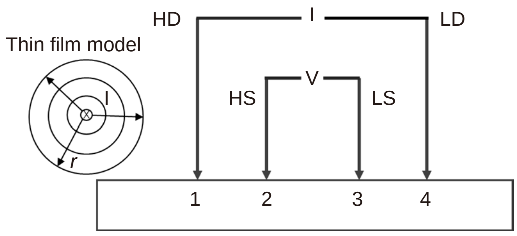

Fig. S1 | The schematic of the four-probe method of sheet resistance. H/LD: High/Low drive, H/LS High/Low sense.

The probe used in the electrical measurement system was a gold-plated tip with spring, as shown in Fig. S2. The needle diameter was 250 μm and the tip diameter was 20 μm. The tip distances of the four probes were measured under the optical microscope, where r_{12}=650 μm, r_{13}=1318 μm, r_{42}=1218 μm, and r_{43}=550 μm. The distance between any two probes was much larger than the film thickness (185 nm), and the thin film model was suitable for the measurement of sheet resistance[S3,S4]. The thickness factor of the film was corrected during the measurement[S5].

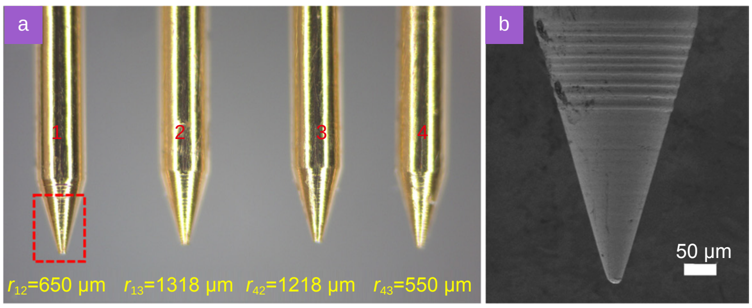

Fig. S2 | (**a**) The optical image of 1 to 4 probe arranged in parallel. (**b**) The enlarged SEM image of the tip of probe 1 in the red square.

To verify the accuracy of the four-probe method, a series of samples with known sheet resistance were selected, and the measurement results were compared with the nominal value, as shown in Fig. S3. The measurement results show clearly the four-probe method works well.

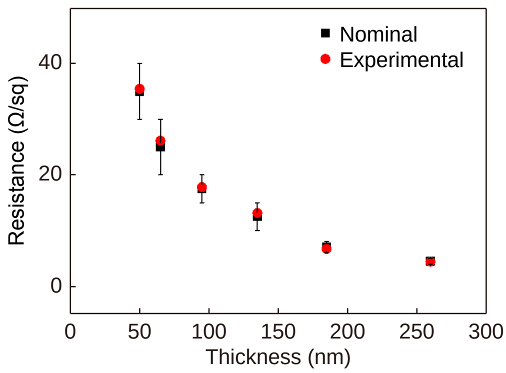

Fig. S3 | Comparison between the actual measured sheet resistance and the nominal value of ITO films with different thicknesses.

Section 2: Nanowire resistance measured by the dual-probe method

Compared with the four-probe method, the dual-probe method was simpler and more suitable for the microscopic measurement based on Ohm's Law. Figure S4 shows the experimental setup of the dual-probe method of a single nanowire. The four pins of the micro-resistance measuring instrument were drawn out through two wires, of which HD (High Drive) and HS (High Sense) were short-circuited, and LD (Low Drive) and LS (Low Sense) were also short-circuited.

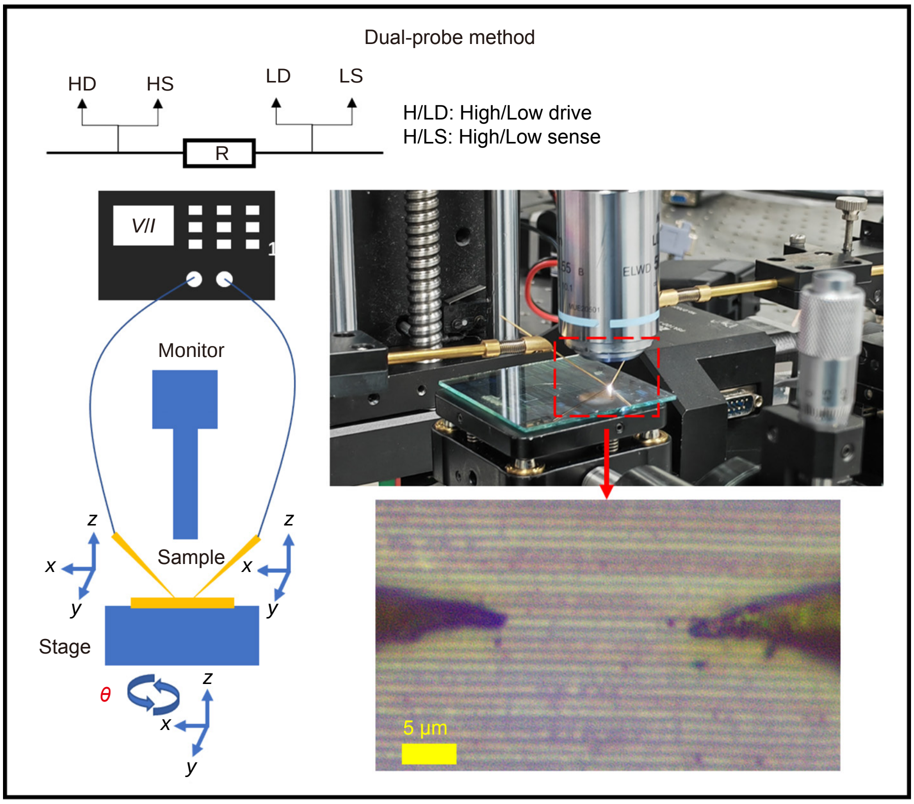

Fig. S4 | The schematic of the dual-probe method, and the experimental setup.

The two probes were connected to the wires drawn from the port, and were respectively fixed on two 3-dimensional translation stages. The high-magnification microscope mainly consisted of a 50× telephoto objective (ELWD 50×, 0.55NA, Nikon) and a charge-coupled device (CCD). It observed in real time the movement of the probe-tip and the connection to the nanowire. The sample was placed on a $x/y/z/\theta$ stage. It could be rotated so that the nanowires were precisely parallel to the line of the two probe-tips. During the measurement, the two probe-tips can respectively precisely touch two points of a single nanowire, as shown in the inset in Fig. S4. The instrument outputs microcurrent (10~100 μA) according to different gears, and simultaneously measured the voltage difference between the two ends. The displayed value was the resistance across the two probe-tips

The probe used was a gold-plated tungsten steel probe, with the tip diameter of 500 nm, as shown in Fig. S5. The contact resistance was about 50 mΩ, which was less than 10^{-4} in magnitude compared to the resistance of the nanowires in the experiments. Therefore, the dual-probe method did not bring errors to the experimental results of a single nanowire resistance.

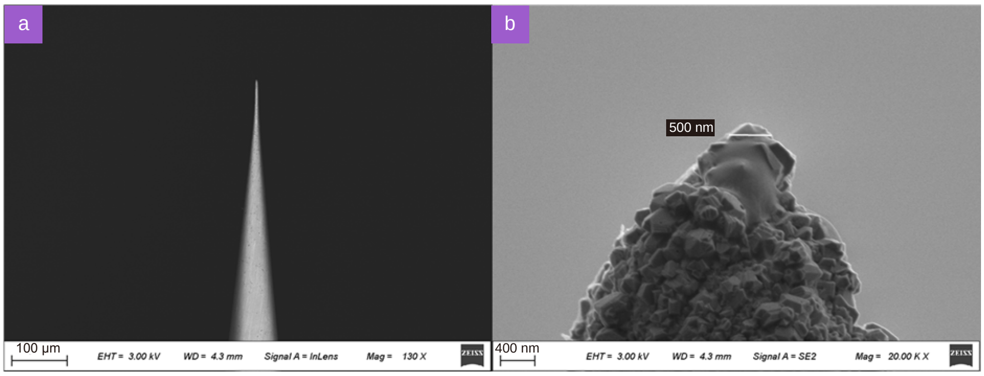

Fig. S5 | SEM image of the probe. (**a**) Full view, and (**b**) the enlarged view of the needle tip. The contact diameter of the needle tip is 500 nm.

Section 3: Conductivity calculation of a single nanowire

Figure S6 shows the schematic of the measurement of single nanowire resistance, where L is the distance between two probe-tips, I is the current output by the instrument. W is the width of the nanowire measured by scanning electron microscopy, and H is the height measured by the confocal optical microscope. The cross-sectional area (S), the volume (V), and the resistivity of the nanowire can be calculated by using the following equations, respectively.

$$S=\int_0^W H\mathrm{d}x, \tag{S1}$$

$$V=\int S\mathrm{d}l=\iint H\mathrm{d}x\mathrm{d}l, \tag{S2}$$

$$\rho=\frac{RS}{L}. \tag{S3}$$

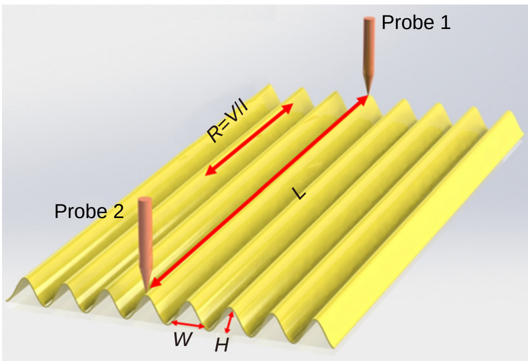

Fig. S6 | The schematic of the measurement of single nanowire resistance. *L* is the distance between two probe tips. *H* is the height, and *W* is the width of the nanowire. *R* is the resistance measured by dual-probe method.

After laser direct writing with a fluence in the range of 0.510~0.637 J/cm², the LSFL nanowires were uniform, and were insulated between each other, as shown in Fig. S7.

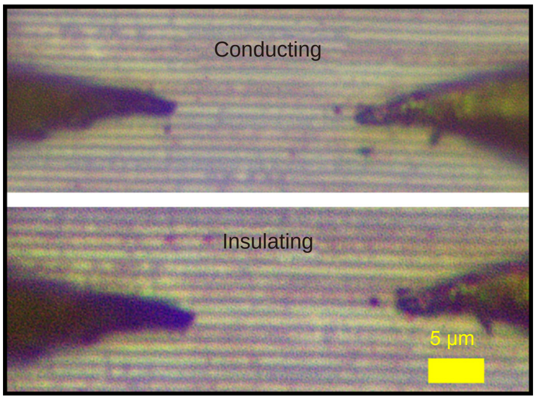

Fig. S7 | Nanowires insulated from each other.

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