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Manipulating InAs nanowires with submicrometer precision

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InAs nanowires are grown epitaxially by catalyst-free metal organic vapor phase epitaxy and are subsequently positioned with a lateral accuracy of less than 1 μm using simple adhesion forces between the nanowires and an indium tip. The technique, requiring only an optical microscope, is used to place individual nanowires onto the corner of a cleaved-edge wafer as well as across predefined holes in Si_3N_4 membranes. The precision of the method is limited by the stability of the micromanipulators and the precision of the optical microscope. © *2011 American Institute of Physics*. [doi:10.1063/1.3657135]

Semiconducting III-V nanowires are of growing interest for nanoelectronic, nano-optical, and nanomechanical applications[1–8] and even for topological quantum computing.[9] For these more advanced applications like the latter, a high precision is required for the positioning of nanowires, absolute and relative to each other. However, experimental techniques for this task are scarce. Typically, the nanowires are distributed randomly on a substrate, e.g., by using a dry cleanroom wipe which mechanically picks up some nanowires. Afterwards, the nanowires are partly left on a surface by pressing the wipe onto it.[10] In another technique, nanowires are removed from the growth substrate by ultrasonication, and the solution is subsequently drop cast onto a target material.[11,12] After such deposition procedures, adequate nanowires are searched for in an electron microscope or an atomic force microscope. These techniques are neither precise nor scalable. A more controlled positioning method uses a high frequency electric field between two contacts within a liquid/nanowire solution. This aligns some of the wires between the electrodes before the solvent is vaporized[13,14] and results in nanowires parallel to the electric field. But the success rate is lower than 50% (Ref. 15) and the method does not allow arbitrary angles between the nanowire and electrodes. The most accurate method so far uses a nanotweezer inside a scanning electron microscope (SEM). This technique achieves a precision down to 10 nm (Ref. 16) and can even grab low diameter objects as multiwall carbon nanotubes.[17,18] Another possibility is to use a tungsten tip inside the SEM, nano-weld a selected nanowire at the tip by e-beam deposition of platinum, and, subsequently, move the nanowire away from the growth substrate.[19,20] To place the nanowire at the desired position, it is cut by focussed ion beam irradiation and thereby released from the tip. Both SEM methods have the drawback of being time-consuming and expensive. Moreover, they can damage or contaminate the nanowire surface. More elegantly, Kjelstrup-Hansen *et al*. used lithographically prepared microcantilevers[21] to grip individual nanowires under an optical microscope using adhesion forces. The nanowires are then placed onto another cantilever for electrical and electromechanical measurements.[22] Here, we demonstrate an even simpler method which relies on an In tip shaped under ambient conditions to pick and place single InAs nanowires with less than 1 μm precision. This novel technique completely avoids electron microscopes and electron beam lithography and is, thus, easy to implement. It allows picking up nanowires which are optically visible down to diameters of 20 nm (Ref. 22) with a length down to 2 μm and, subsequently, placing them onto a target substrate with submicrometer precision.

The setup is shown in Fig. 1. It consists of an optical bright field microscope[23] with a cross table and a temperature-controlled heater. Two objective lenses leading to hundredfold and thousandfold magnification are available at working distances of 17.6 mm and 4.6 mm, respectively. Two micromanipulators with a nominal spatial accuracy of 1 μm (Ref. 24) are attached to the base plate of the microscope. The heater which is used to produce indium tips is fixed on the cross table.

The preparation of the In tips is similar to their preparation for In microsoldering:[25,26] A sharp etched tungsten tip similar to those used for scanning tunneling microscopy[27] is clamped into the tip support of the micromanipulator. A small piece of In is placed onto a cleaved fragment of a silicon wafer mounted on the heating plate. The temperature is set to 170 °C in order to melt In. Then, the tungsten tip is dipped into the In droplet and removed by shifting the cross table by about 2 mm/s. This results in In tips with several millimeters in length. Figure 2(a) shows a SEM image of such an In tip demonstrating the typical radii at the apex of about 150 nm. The shape of the tip is largely reproducible, but depends on the droplet temperature and the velocity of the tungsten tip during removal from the In droplet.

For manipulation, undoped InAs nanowires with diameters of ~100 nm were selectively grown by catalyst-free metal organic vapor phase epitaxy (MOVPE).[28] Preconditions

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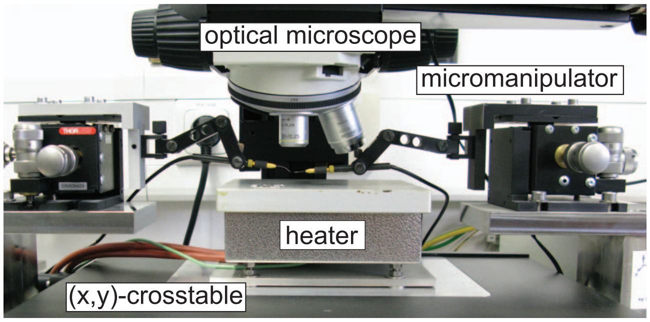

FIG. 1. (Color online) Setup of the manipulation stage consisting of a commercial optical microscope (Leica DM 2500 MH), two (x, y, z) micromanipulators (Thorlabs), and a heating stage mounted onto a cross table.

for manipulation within the optical microscope are nanowires with a length of more than 2 μm and a relative distance on the growth substrate of more than 500 nm. In general, it is easier to lift longer nanowires with larger relative distances.

To remove individual wires, the In tip is first placed next to a wire as shown in the optical microscope image of Fig. 2(b). The wires, which stand perpendicular to the surface, appear as black dots. Next, the In tip is pushed against the wire, such that the wire breaks somewhere between the contact point of the In tip and the substrate. The broken nanowires either directly stick to the In tip, or mostly, jump several μm away. However, in more than 80% of these cases, the wires are tilted with respect to the substrate with only a small contact area between the wire and the substrate. The wire can now easily be picked up by gently touching it with the In tip which provides larger contact area with the wire than the substrate and, thus, larger adhesion forces. Then the nanowire is aligned with the focus plane of the microscope by rotation of the In tip and, thus, becomes sharply visible (Fig. 2(c)).

In order to place the wire onto a substrate, the In tip is approached step by step towards the desired position. The

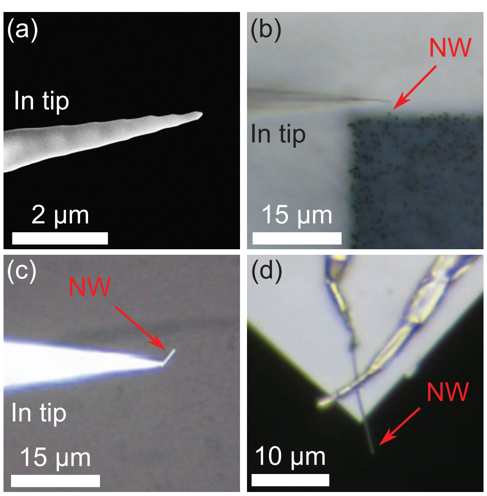

FIG. 2. (Color online) (a) SEM image of the end of an In tip (apex radius $r \approx 180$ nm). (b) Optical image of an In tip approached to a field of InAs nanowires with 1 μm pitch; the nanowire to be captured is marked by an arrow. (c) Same nanowire at the In tip after the pick-up procedure. (d) Nanowire of length $l \approx 15$ μm placed onto the corner of a cleaved GaAs wafer and contacted twice by In microsoldering[25,26] (enhanced online). [URL: http://dx.doi.org/10.1063/1.3657135.1]

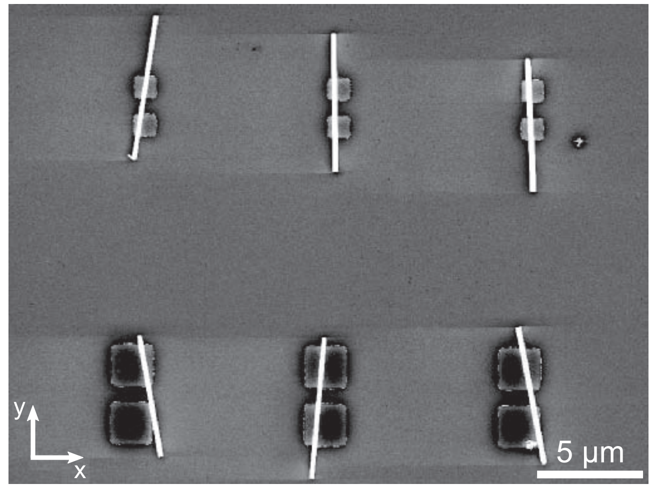

FIG. 3. SEM image of InAs nanowires placed on top of Pt contacts; averaged accuracy: $(\Delta x, \Delta y) = (0.6, 0.9)$ μm lateral, $\Delta\alpha = 9^\circ$ angular.

substrate can be rotated for the sake of alignment of the wire with a predefined structure on the surface. To achieve highest accuracy in positioning, the focus plane of the microscope has to be switched back and forth between the substrate and the approaching In tip. As soon as the nanowire touches the surface, it permanently sticks to that position because of the larger contact area between the wire and the substrate than between the wire and the In tip. Thus, lateral and rotational alignment has to be achieved prior to touching the surface. Typically, the whole procedure to pick up and place a nanowire lasts about 5–10 min being slightly longer for very short wires.

Figure 2(d) shows a wire placed onto the corner of a GaAs wafer, cleaved twice in perpendicular directions in order to provide a sharp corner. Subsequently, two In contacts are microsoldered to the wire[25,26] under the same optical microscope. Such an arrangement can be used, e.g., as a tip for scanning tunneling microscopy, where it might be helpful to have conductive tips with an increased screening length, in order to probe long-range electron-electron interaction effects.[29] Importantly, the whole preparation requires only an optical microscope, standard micromanipulators, and a heating stage and is, thus, very easy to implement.

In order to determine lateral and angular accuracy of the method, a Si/SiO_2-wafer has been structured with a number of pairs of Pt contacts, 35 nm in height. The two contacts of a pair have a distance of 750 nm and the contact areas are (1×1) μm^2 and (2×2) μm^2. Figure 3 shows a SEM image of nanowires which are placed as accurately as possible on the center of a pair of contacts. Notice that all wires touch both contacts. The lateral accuracy in x and y direction turns out to be, on average, 0.6 μm and 0.9 μm, respectively. The angular accuracy was 9° on average.

Besides production of nanowire STM tips (Fig. 2(d)), we use the method to construct suspended nanowire devices by placing the wires across holes of a perforated Si_3N_4 membrane.[30] The suspended nanowires are contacted with Ti/Au electrodes defined by electron beam lithography. This allows, e.g., inspection of the contacted wire by transmission electron microscopy or bending of the wire by

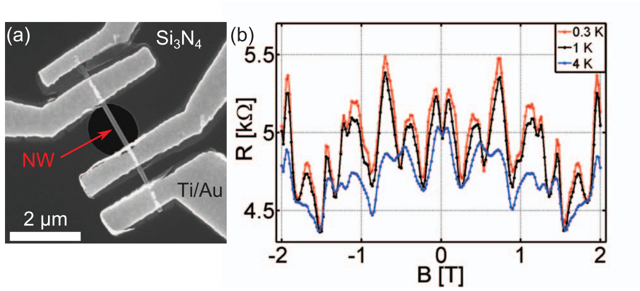

FIG. 4. (Color online) (a) SEM image of an InAs nanowire positioned across a hole within a Si_3N_4 membrane. The wire is contacted by four Ti/Au electrodes. (b) Magnetoresistance of this nanowire recorded by a four-terminal measurement at different temperatures as indicated.

applied electrostatic forces during transport measurements. Figure 4(a) shows a SEM image of a suspended, slightly *n*-doped InAs nanowire with four Ti/Au contacts. The wire is grown by catalyst-free MOVPE.[28] The partial pressure ratio between Si_2H_6 and TMIn was 7.5×10^{-3} in order to dope the wire. Wires from the same growth procedure were transferred to a Si/SiO_2 wafer and contacted for field-effect measurements. This revealed a mobility of roughly 1000 cm^2/Vs and a carrier concentration of 2×10^{18} cm^{-3} which is typical for InAs nanowires.[8,31,32] The four-terminal magnetoconductance measurements of the suspended wire are performed by a lock-in amplifier providing an ac current signal to the outer contacts with an amplitude of 5 nA and a frequency of 17.3 Hz. The voltage drop across the inner contacts is measured. Figure 4(b) shows the resulting, reproducible universal resistance fluctuations of the wire for three different temperatures. The average resistivity of the wire turns out to be $\rho = 4.4 \times 10^{-5}$ Ωm very similar to $\rho = 3.1 \times 10^{-5}$ Ωm found for the corresponding InAs nanowires on Si/SiO_2 for the same growth run. The resistance fluctuations of 10% are also similar to previous experiments on InAs nanowires.[33,34] More detailed results using this sample will be published in Ref. 35.

Further future applications of this novel method might include placing nanowires at specific positions for easier localization with a scanning probe microscope or the construction of geometrical networks of nanowires as, e.g., T-junctions, which are proposed for exchange operations of Majorana fermions.[9]

In summary, we have demonstrated an easy to implement method to place single nanowires onto desired positions with a lateral accuracy below 1 μm and an angular accuracy of 9°. The method requires only an optical microscope, a micromanipulator, and a heating stage providing 170 °C.

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