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Fabrication of one-dimensional devices by a combination of AC dielectrophoresis and electrochemical deposition

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Abstract
We demonstrate a hybrid process for fabricating one-dimensional wire devices. The process is a combination of an alignment procedure using dielectrophoresis and subsequent contact metal formation utilizing electrochemical deposition with non-toxic organic-based Au electrolytes. Several devices have been successfully made from GaN nanowires or multi-walled carbon nanotubes (MWCNTs) using our hybrid technique. We demonstrate that rapid thermal annealing improves the ohmic characteristics by five orders of magnitude in the case of the GaN devices and ∼300% in the case of the MWCNT devices. One of the reasons for this improvement is enhanced gold wetting due to the reduction of grain size at the annealing temperature.

1. Introduction

Recently there have been efforts to utilize one-dimensional (1D) materials such as semiconductor nanowires and carbon nanotubes (CNTs) in the realization of field effect transistors, optical devices, bio-sensors, and flexible devices [1–6]. There are two main technical issues in fabricating these 1D devices. First, it is difficult to reliably align these 1D materials in designated positions. Second, it is important to form reliable ohmic contacts. To overcome the first problem, there have been various novel approaches such as a lithographic definition of a catalyst and subsequent growth [7], the utilization of fluidic force [8], vertical growth [9], electrical manipulation [10, 11], the utilization of self-assembled monolayers [12], and the Langmuir–Blodgett method [13]. Reduction of contact resistance has been achieved by finding an adequate metal [14] and by forming a certain compound by annealing [15]. New processes for contact formation such as ion-beam lithography [16] and large area electroplating [17] have been developed. A systematic study of the relation between the contact resistance and the thickness of the contact metal has also been completed [18]. As far as we know, the alignment and contact formation problem in the same device but on a nanometer scale have rarely been studied.

In this paper we describe a method to align 1D materials and to subsequently form reliable ohmic contacts using combined, serial processes of dielectrophoresis and electrochemical deposition. We performed the alignment by dielectrophoresis. The contact formation was done by electrochemical deposition. We used GaN nanowires and bundles of MWCNTs to demonstrate this hybrid process.

2. GaN nanowire alignment and electrochemical deposition

Figure 1(a) shows schematic procedures for forming electrical contacts on a nanowire using dielectrophoresis and subsequent electrochemical deposition. Figure 1(b) shows a schematic

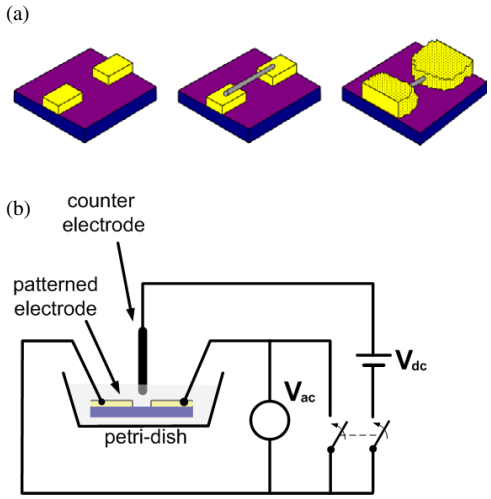


Figure 1. (a) Schematics describing the capture of nanowires using dielectrophoresis and contact formation using electrochemical deposition and annealing. (b) A schematic diagram of the experimental setup.

experimental setup of the dielectrophoresis/electrochemical deposition. We positioned a substrate with a pair of nano-gap electrodes in a Petri dish. We then applied a drop of solution containing 1D wire materials. The typical concentration of 1D wires corresponded to two or three nanowires in an area of $40 \times 40\ \mu m^2$ after natural drying of a 0.1 μl drop of the liquid containing those wires. The alignment of nanowires using dielectrophoresis was performed with the switch in figure 1(b) open. We then applied AC voltage pulses with peak-to-peak value (V_{pp}) ranging from 1 to 15 V. The frequency ranged from 0.1 to 10 MHz. The typical duration of the AC voltage is from 1 to 5 s. After a gentle blow-dry of the wire solution drop, we introduced an electrolyte solution into the Petri dish so that the counter electrode as well as the substrate were fully immersed. The contact deposition was then performed with the switch of figure 1(b) closed.

The geometry of the electrodes was optimized for better capture and alignment using three-dimensional electromagnetic field simulation. Figures 2(a) and (b) show the distributions of electric field magnitude ($|\mathbf{E}|$) and the gradient of the electric field amplitude squared ($\nabla|\mathbf{E}|^2$), respectively. The magnitudes of $|\mathbf{E}|$ and $\nabla|\mathbf{E}|^2$ are maximum in the red region and minimum in the blue region. The rectangular electrode shown in figure 2 exhibits a maximum $\nabla|\mathbf{E}|^2$ at both corners and a minimum $\nabla|\mathbf{E}|^2$ in the middle of the edge facing the other electrode. The nanowires were extracted towards the electrode edge by large $\nabla|\mathbf{E}|^2$, then stayed in the middle with the minimum $\nabla|\mathbf{E}|^2$ [19].

The GaN nanowires used in the experiment were synthesized by a chemical vapor deposition technique [20]. These nanowires had typical lengths of 1–1.5 μm and diameters of 40–80 nm. Nano-gap electrodes of Ti/Au = 10/70 nm were patterned on SiO_2/Si substrates using a standard electron beam lithography and lift-off process. The oxide layer was thermally grown and the thickness was 300 nm. The typical size of the nano-gap was 800 nm to match the typical length of the

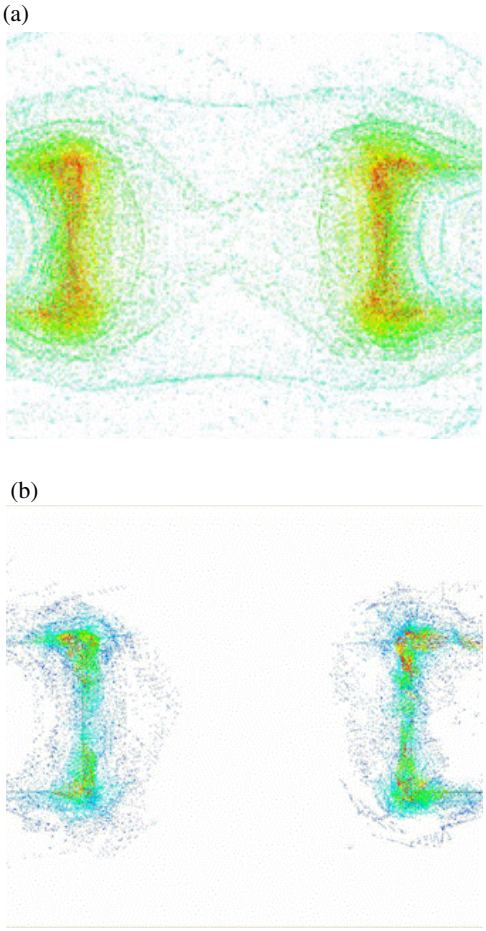


Figure 2. (a) The calculated distribution of the magnitude of the electric field ($|\mathbf{E}|$) near the nano-gap electrodes. (b) The calculated distribution of the gradient of the electric field magnitude squared ($\nabla|\mathbf{E}|^2$) near the nano-gap electrodes.

nanowire. Alignment of the nanowire was performed by dropping a 0.5 μl GaN nanowire solution on the nano-gap electrodes when square pulses with V_{pp} of 14 V and the frequency of 1 MHz were applied between the electrodes. A gentle blow-dry was completed before the solution evaporated.

Metal contacts were deposited by electrochemical deposition using an organic-based Au electrolyte [21]. The electrolyte solution was made by dissolving 0.3 g of potassium iodide (KI) and 0.3 g of iodine (I_2) in 10 ml isopropyl alcohol. A gold wire with a diameter of 50 μm was dipped and the solution was stirred for 2 h at 80 °C until Au saturation occurred. Both KI and I_2 are the sources of medical iodine tincture. They are safer and more cost-effective than the conventional cyanide-based Au electrochemical solution [22]. The bias on the Au counter electrode was fixed at 0.1 V relative to the patterned Ti/Au electrode pairs. The bias current was ~40–60 μA and the deposition time was approximately 10–15 s. Finally, isopropyl alcohol rinsing was done to prevent further deposition and erosion by the residual solution. The amount of Au reduced onto the nano-gap electrodes was proportional to the current density [23] so that most of the reduced Au was attached on the edges of the nano-gap electrodes.

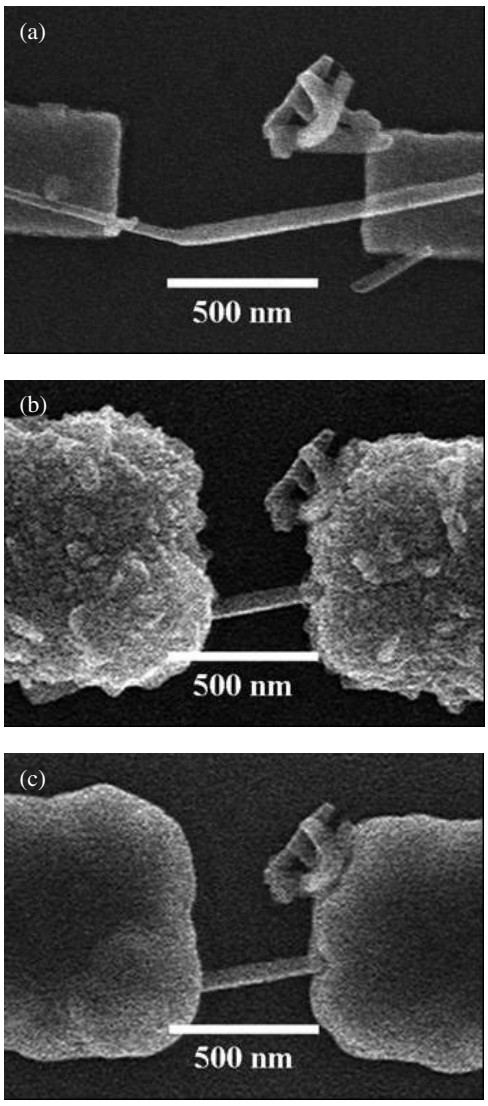


Figure 3. (a) A SEM image after capturing a single GaN nanowire by dielectrophoresis. (b) A SEM image of the device after electrochemical deposition. (c) A SEM image of the device after RTA.

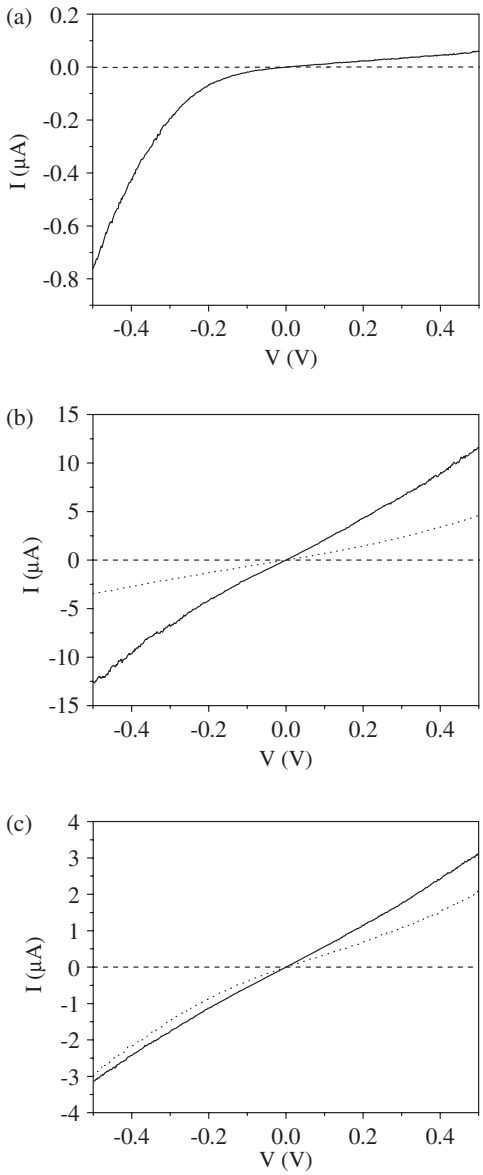


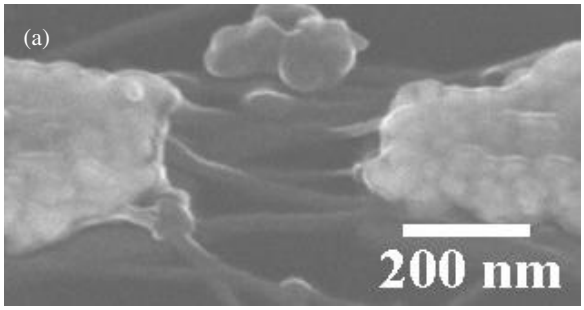
Figure 4. (a) I–V characteristics measured from the device pictured in figure 3 after electrochemical deposition (dashed line) and after RTA at 600 °C (solid line). (b), (c) I–V characteristics measured from other devices, fabricated using the same procedure, after electrochemical deposition (dashed line), after RTA at 550 °C (solid line), and after RTA at 700 °C (dotted line).

Figures 3(a) and (b) show a GaN nanowire after the dielectrophoresis step and after the electrochemical deposition step, respectively. We can clearly identify that the edges of the nanowire on the electrodes were completely covered by the electrochemical deposition.

3. Current–voltage characteristics of the GaN nanowire

The nanowire device was not conducting after the electrochemical deposition since the size of the Au grains deposited on the nanowire edges was too large to wet the entire surface of the wire, as shown in figure 3(b). Therefore, rapid thermal annealing (RTA) in a vacuum was performed at 550–600 °C for 45 s of ramping time and 15 s at the target annealing temperature. Figure 3(c) shows an image of the device after the RTA step. A much smaller grain size can be observed. High annealing temperatures were also expected to help break the native GaO_x surface [24].

Figure 4(a) shows current–voltage (I–V) characteristics measured from the fabricated device. The dashed line denotes the I–V characteristics before RTA and the solid line denotes the I–V data after RTA at 600 °C. The current level measured from the device after RTA is five orders larger than that obtained before RTA. The observed diode-like I–V characteristic in figure 4(a) could originate from the structural kink which is denoted by the arrow in the SEM photo of figure 3(a). A more realistic scenario would be the formation of Schottky barriers with different barrier heights at the source and the drain contact [25]. Figures 4(b) and (c) show I–V



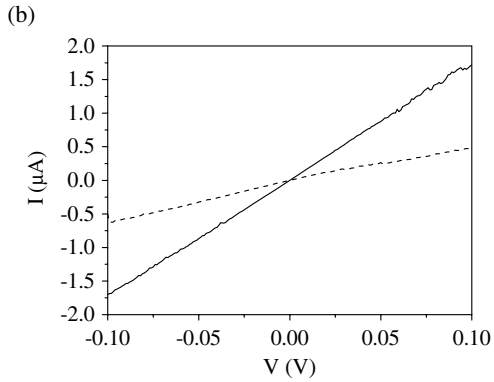


Figure 5. (a) A SEM image of a MWCNT device using our dielectrophoresis/electrochemical deposition method. (b) The I–V characteristics measured from the device after electrochemical deposition (dashed line) and after RTA at 450 °C (solid line).

taken from two other single wire devices fabricated using the same procedure. The dashed, solid, and dotted lines denote the data measured before RTA, after RTA at 550 °C, and after RTA at 700 °C. The I–V from 550 °C RTA devices show almost linear behaviors. The current became at least 10% smaller in 700 °C RTA devices. The reason for this reduction in current might be the reduction of the contact area from the interfacial deterioration during excessively high temperature thermal cycling. The discrepancies in the current levels of figure 4(b) from that of figure 4(c) come from the size difference of the GaN nanowires.

4. Contact formation using MWCNTs

Our method can be applied in the fabrication of CNT devices. Figure 5(a) shows a SEM image of the device where several bundles of MWCNTs bridged nano-gap electrodes. The same procedure as that for the GaN nanotube device was used, except $V_{pp} = 1$ V in this case. It was noticeable that the CNTs were bent downwards. This suggested that the CNT was more flexible than GaN nanowires [26, 27]. Figure 5(b) shows the I–V characteristics measured from the device before RTA (dashed line) and after RTA at 450 °C (solid line). While the device after RTA exhibited a larger current, the device even before RTA still showed an appreciable current. This current resulted from a large electron affinity between CNT and Au and from good wetting properties.

5. Conclusions

We described a new and unique method for aligning 1D materials and subsequently forming reliable ohmic contacts using series processes of dielectrophoresis and electrochemical deposition. We performed the alignment by dielectrophoresis and the contact formation was accomplished by electrochemical deposition. We used GaN nanowires and bundles of MWCNTs to demonstrate the process. We obtained good ohmic characteristics from all of the fabricated devices.

Acknowledgments

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