

***In situ* nanointerconnection for nanoelectronics via direct auto-catalytic lateral growth**

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The lateral reduction of interconnection in nanoelectronics will require a one-dimensional metallic nanointerconnector. This work presents an achievement of the all-chromium (Cr) nanointerconnection architecture, an approach to nanointerconnection, in which both electrodes and connecting lines are realized by the same Cr using the autocatalytic function of Cr without any additional lithography. Especially observed was the time evolution of the directional lateral growth of Cr nanowires using a dc electric field during the *in situ* growth of Cr nanowires. Finally, it was confirmed that the *in situ*-grown Cr nanobridge could act as an electrode interconnector due to its good metallic current-voltage characteristics. © 2005 American Institute of Physics. [DOI: 10.1063/1.1915530]

The use of nanowires for electronics applications has been demonstrated in a number of fascinating experiments. One of the most obvious and promising applications of nanowires is as interconnectors in future integrated nanoelectronics and actuators. The speed and electrical performance of nanochips are mainly limited by the interconnections between different metal layers and the vertical interconnection through vias.¹⁻⁸ In this regard, carbon nanotubes may be promising candidates as interconnection materials in dimensions below 50 nm, and their selective growth at a desired position through either lateral or vertical growth via hole technology has been reported.^{2,9} Another approach is to achieve assembly of nanowire (and/or tube) fluidic flow directed assembly with or without electric field. In this method, nanowire or tubes can be easily aligned by passing a suspension of nanowires through microfluidic channel structures.¹⁰ Fluid flow directed assembly method based on the shear flow mechanism^{11,12} has some limitations, including the need for preparation of microfluidic channel structure, the contamination effect of suspension on the predefined understructure, and incompatibility with the conventional semiconductor process,

In this work we present the *in situ* interconnection of two adjacent electrodes by a metallic nanobridge, which functioned as an auto-catalyst¹³ during the one-dimensional nanostructure process. Especially introduced during the growth was a dc bias field to effectively assist in the longitudinal growth of the metallic bridge starting from the opposite side of the electrodes. In this case, Cr bridges, floated in air and suspended between patterned Cr electrodes, were made to cross between the autocatalytic Cr's electrodes using the rapid thermal chemical vapor deposition (RTCVD) method⁹ at the relatively low process temperature of 750 °C. In the experiment conducted, a layered structure was prepared by sequentially stacking SiO₂ and Cr layers on a doped

Si substrate. A key technique of this method was to employ the autocatalytic Cr materials as active interconnectors and to use one of the electrode terminals as a via hole to connect the upper with the lower chip layers. The typical process is as follows. The 1- μ m-thick SiO₂ layer was grown on the *n*-type heavily doped Si wafer through the conventional dry oxidation process at 1100 °C, followed by the deposition of the about 100-nm-thick Cr catalytic film through the dc sputtering method using Ar plasma. Only one-step photolithography was adopted to define the patterns before the growth of an entire *in situ* junction. The RTCVD chamber temperature was rapidly raised to the process temperature of 750 °C within about 10 min using halogen lamps, after evacuation down to 10⁻² Torr. During the direct lateral growth, the total pressure of the chamber was kept constant at 10 Torr, while the total flow rate of process gases of Ar+C₂H₂+H₂ was maintained at 150 sccm. To apply the electric bias, two specially designed probes were prepared to which patterned electrodes were attached via a metallic paste. After about 2 min growth under biasing dc voltage, the chamber was continuously purged with a mixture of H₂ and Ar until the chamber temperature went down to the room temperature. The total processing time for the interconnection was 15–50 min. All the fabricated junctions were examined using a field emission scanning electron microscope (SEM) (Hitachi S4300), and compositional analysis was performed using energy-dispersive spectra. The electrical properties of the Cr–Cr wire–Cr junction were evaluated by Keithley 236 Unit.

Figure 1 shows a typical SEM image of the *in situ*-grown metallic Cr nanorods on SiO₂-coated Si substrates. Short Cr nanoneedles were frequently observed in the whole area of Cr film and formed very dense. Normally the Cr nanoneedles that were formed on the Cr films after the CVD process, which acted as autocatalysts, were longer than the as-deposited Cr film, the thickness of which was reduced. This result indicates that Cr nanoneedles originate from Cr films instead of growing from thin films via auto-catalytic function under a working gas atmosphere. The absence of

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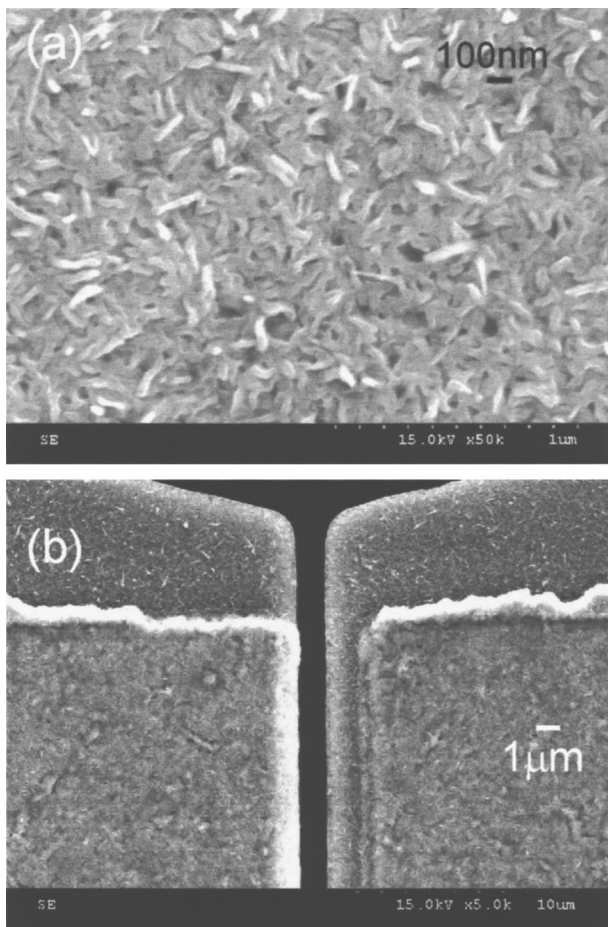


FIG. 1. (a) An extended view of a typical Cr nanowire sheet grown on Cr-coated SiO₂-Si substrates using the autocatalytic function. (b) A patterned growth of Cr wires via the autocatalytic function of a layered Cr/SiO₂ film before biasing. Here SiO₂ in Cr/SiO₂ was used to raise up the patterned structure, which was effective to prevent Cr needle from adherence to the substrate afterwards. Dark region between the patterned Cr electrodes is SiO₂ which was covered the whole area.

feedstock gases for Cr growth supports the above interpretation. It also shows, however, that the Cr needle growth mechanism is not yet fully understood.

As a result of applying the autocatalytic function of Cr on the direct interconnection between the electrodes, an *in situ*-grown metallic Cr nanobridge was obtained between two Cr contact electrodes. Figure 2 shows the growth of the Cr nanointerconnector with the time evolution. To investigate the growth behavior of the autocatalytic layer, images were monitored at different growth times. Some interesting points were found, which suggested a probable mechanism for the nanomaterial growth from the self-catalytic layer used in this work. First, the bulk of the patterned Cr electrode was activated under the mixture gas [as shown in Fig. 1(a)]; then, the nanostructure (see Fig. 2) protruded at an early stage of its lengthening towards the opposite Cr electrode at the edge of the Cr pattern, after which a nanowire with a needle-like end was developed to connect the wires that bridged the gap in the gas environment used in this work. The nanochannels under these conditions were kept very straight during the growth with the help of the dc electric field. The nanobridges with filled inner areas consisted of very sharp rod shapes with triangular tops and nearly perfect straight bodies, and the majority of the materials were 20 nm in diameter with neat surface appearances [Fig. 2(b)]. The associated compo-

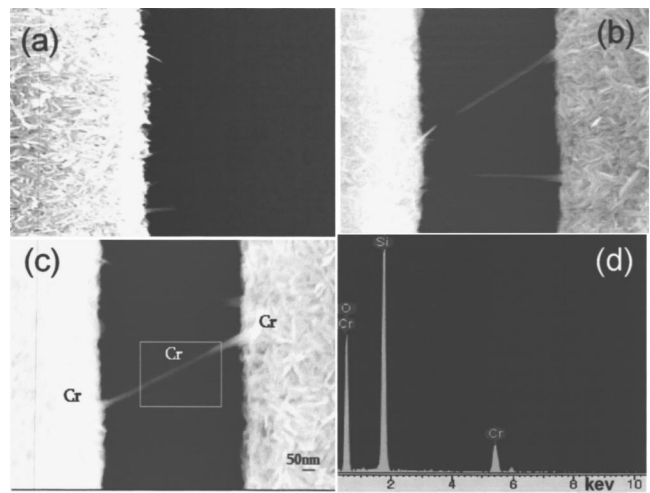


FIG. 2. SEM images of the *in situ*-grown metallic Cr nanobridge between two Cr contact electrodes with the time evolution. (a) The bulk of the patterned Cr electrode was activated under the mixture gas, after which the nanostructure (see figure) protruded at the early stage of its lengthening towards the opposite Cr electrode at the edge of the Cr pattern, (b) the nanowire with a needle-like end developed to the wires that bridged the gap in the gas environment, and (c) the nanochannels under these conditions were kept very straight during the growth with the help of a dc electric field. (d) The compositional analysis of the bridge shown in (b).

sitional analysis in the marked region was performed as shown in Fig. 2(c) by using energy dispersive x-ray analysis. The spectra based on the SEM study indicate that the nature of the nanobridge is metallic chromium. When the growth time increased from 2 minutes the growth density of the Cr nanobridge increased, although the degree of the areal density could be controlled mostly by the dimensions of the lithographically patterned electrodes at the initial preparation process. This kind of enhanced evolution of the Cr nanointerconnector between the electrodes was attributed to a surface-bound growth mechanism. When the Cr nanoneedles protruded from the electrode, i.e., acted as catalysts, at the initial stage, they were free to rotate before they were pinned to the direction of the opposite electrode. The torque exerted by an electric field on a polarizable cylinder and its associated energy of rotation were calculated using tight-binding methods.¹⁴ The results of the calculation showed that the static polarizability of the metallic cylinder was nearly three orders of magnitude larger than the value of the semiconduc-

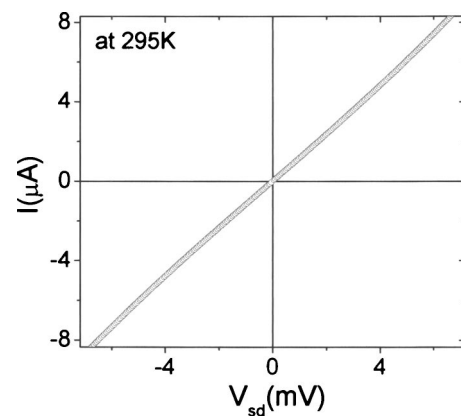


FIG. 3. Current (I)- V (voltage) characteristics of the Cr electrode - Cr nanointerconnector - Cr electrode junction, showing good ohmic behavior at low bias regime.

tion cylinder, and that the metallic cylinder that was shorter than $1.5 \mu\text{m}$ could be easily aligned by the electric field at the process temperature of about 800°C . Although the conclusive or exact growth mechanism in this work cannot be provided, the Cr nanoneedles that initially protruded from the autocatalytic Cr electrode were easily directed towards the opposite electrode in principle and achieved in experiment through our work.

As a final checkpoint, the I - V characteristics of the directly formed junction, such as the patterned electrode (Cr) - suspended Cr nanowire-patterned electrode (Cr), were measured. The typical metallic I - V characteristics, shown Fig. 3, without the effect of gate bias voltage were clearly observed, and the estimated resistance of the single nanointerconnection was about 700Ω . The low resistance value suggests that good contact due to the formation of an *in situ* junction through autocatalytic action can contribute a possible route to interconnection.

In summary, this letter introduced the *in situ* nanointerconnection technology as a promising high-level integrated nanoelectronics and moletronics technology, using the direct lateral growth method based on the one-step autocatalytic function.

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