# SUPPLEMENTAL

# Abrupt Schottky-Junction in Epitaxial Al/Ge Nanowire Heterostructures

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In the following we will give a detailed description of the annealing process leading to the Ge exchange reaction by Al, including a movie as well as details on the temperature dependent resistivity measurements of the fully exchanged and thus pure Al nanowire.

## In-situ SEM monitoring of exchange reaction

The successive exchange of Ge by Al can be monitored and even controlled in situ when the annealing is performed in a SEM system with a heating stage. The movie shows the successive replacement of Ge by Al at an annealing temperature of T=623K in 12x time-lapse.

## Ge replacement reaction – influence of annealing temperature, duration and NW diameter

### Influence of annealing temperature:

The Ge replacement in the NW due to Al diffusion requires a minimum annealing temperature of about T=600K. Below this temperature no Ge replacement by Al was observed within a reasonable time. The optimum temperature which was also used for all experiments discussed in the paper is T=623K. For even higher temperatures the reaction became accelerated and could be hardly controlled. Finally above the eutectic temperature of Ge-Al (T=693K) the wires appeared to be molten though annealing was performed far below the melting temperature of Al (T=933K) and Ge (T=1211K). Figure 1S shows a Ge NW with 2 Al pads annealed at T=723K which leads to an obviously deteriorated NW.

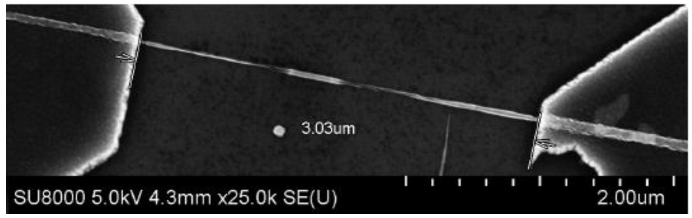


Figure 1S. SEM image of Ge NW with Al pads after annealing at T=693K.

**Influence of annealing duration:**

To demonstrate the time dependency of the Ge exchange reaction we monitored the reaction in-situ in an SEM system equipped with a heating stage. Figure 2S shows images of the Ge NW with an Al pad annealed at T=623K for various process duration in steps of 60s. Under the given experimental conditions the exchange reaction appears to be almost linearly dependent on the processing time.

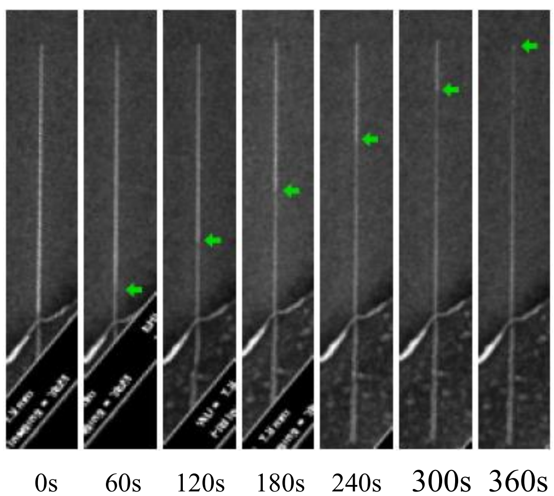


Figure 2S. SEM images of a Ge NW contacted by an extended Al pad after annealing at T=693K for various annealing times as indicated below the SEM images.

**Influence of NW diameter:**

The influence of the NW diameter on the Al-Ge exchange reaction is shown in Figure 3S. Al pads were patterned onto VLS grown Ge NWs with diameters ranging from 20 to 60nm. After a standard annealing procedure at T=623K for 240s in forming gas atmosphere we measured the length of the Al segments. Figure 3S shows thus determined length of the Al extension as a function of the NW diameter. Obviously, that Al exchange of Ge is more effective for thinner NWs. Very similar to our previous work on the formation of copper-germanide enabled by a chemical reaction between metallic Cu pads and VLS grown Ge-NWs[1] with increasing NW diameter the exchange reaction becomes slower and stopped completely for NWs above a certain thickness (>65nm).

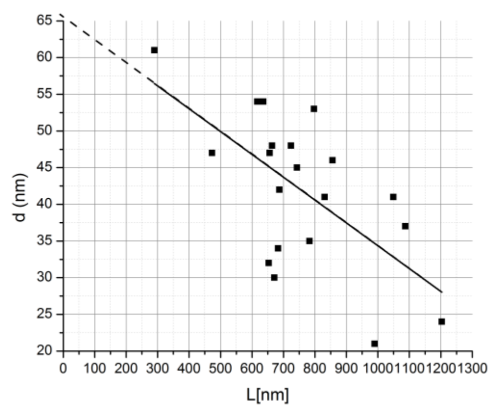


Figure 3S. Length of the Al nanowire segment (Ge substitution length) as a function of the diameter of the pristine Ge NW.

## Exchange reaction of Ge NW covered with 20nm $Al_2O_3$

Figure 4S (a) shows the SEM image of the Ge NW contacted to Al pads. (b) the same NW after annealing at T=623K for 240s demonstrating Ge replacement in the upper part of the nanowire and (c) after full replacement of Ge by Al with the $Al_2O_3$ layer still intact.

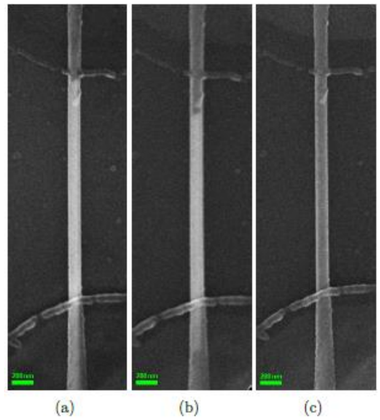


Figure 4S. SEM images of Ge NW with Al pads covered with 20nm $Al_2O_3$ (a) as processed, (b) after annealing at T=693K for 240s and (c) after full replacement of Ge by Al.

## Exchange reaction of Ge NW with small Al pads (small reservoir)

The SEM image in Figure 5S shows the Ge NW connected on one side to a small Al pad. Even after 1800s annealing at T=623K the Ge NW was not fully replaced by Al. As discussed in detail in the paper this is due to the limited Ge solubility of 1.5at% in Al at the annealing temperature of T=623K.

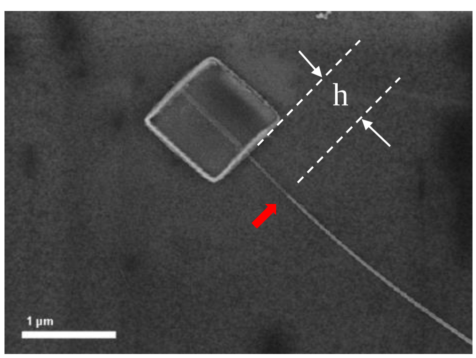


Figure 5S. SEM images of Ge NW with a small Al pad of 1x1$\mu m^2$ and a thickness of 100nm after annealing at T=693K for 1800s. The red arrow indicates the Al/Ge interface.

According to the calculated volume of the Al pad (1x1x0.1μ$m^3$) and the substituted part of the NW (dark) which is assumed to have an hexagonal cross section with a diameter of d=46nm and a length of L=1,7μm the atomic concentration of Ge in the Al-pad is calculated with help of the molar Volume $V_m$ (Formula 1 to 3) to be about 1,68at%.

1. $V_{pad} = 1 \times 1 \times 0.1 \mu m^3$

2. $V_{NW,Ge} = d^2 \cdot \frac{2}{\sqrt{3}} \cdot h = 2.1 \times 10^{-3} \mu m^3$

3. $\frac{V_{pad}}{V_{pad}+V_{NW,Ge}} \cdot \frac{V_{m,Al}}{V_{m,Ge}} = 1.68 at\%$

## Resistivity of the Al NW as a function of temperature

Figure 6S shows the temperature dependent resistivity measurement of a fully replaced and thus pure Al nanowire. As expected for a metallic nanowire the resistivity increases monotonically with temperature. Over the entire temperature range the resistivity of the Al nanowire appeared to be twenty times higher than the tabulated value of bulk Al (green line in Figure 6S).

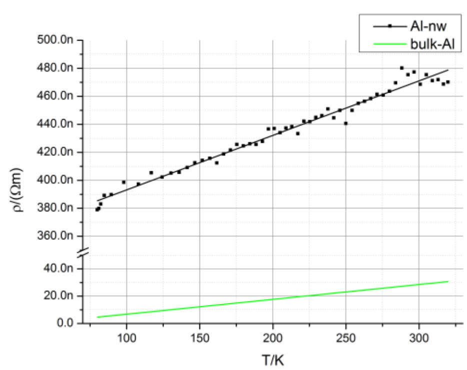


Figure 6S. Temperature dependent resistivity of an Al nanowire.

## Chemical mapping by energy dispersive x-ray spectroscopy (EDX)

Principal component analysis (PCA) treatment was done on the EDX data in order to denoise and remove some artifact signals.[2]

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[1] T. Burchhart, A. Lugstein, Y. J. Hyun, G. Hochleitner and E. Bertagnolli, „Atomic Scale Alignment of Copper-Germanide Contacts for Ge Nanowire Metal Oxide Field Effect Transistors", Nano Lett., 9 (11), 3739 (2009).

[2] F. de la Pena, M.H. Berger, J.F. Hochepied, F. Dynys, O. Stephan, M. Walls, Ultramicroscopy 111 (2011) 169–176.