Electron Beam Lithography of Nanostructures

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After a short description of the hard- and software we have used for making the nanostructures, we report on three activities: i) For Si/SiGe modulation-doped field-effect transistors, we fabricate Schottky gates by a lift-off technique with gate lengths below 100 nm. ii) By exposing arrays of boxes with a side length of less than 70 nm and by transferring them via reactive ion etching into a pre-structured Hall bar we produced antidots for magnetotransport investigations. iii) Oxide-patterned silicon substrates are used as a template for selective molecular beam epitaxy. By combining the prepatterned substrates with Stranski-Krastanov growth of Ge or SiGe layers, self-organized quantum dots can be arranged in a regular pattern for selective excitation or contacting.

1. Introduction

For electron beam lithography of nanostructures on Si/SiGe heterostructures we use a JEOL JSM 6400 scanning electron microscope at an accelerating voltage of 40 keV and Polymethylmetacrylat (PMMA) resists with molecular weights between 50k and 950k a.u. The samples are cleaned in acetone and methanol in combination with ultrasonic. On samples with no oxide layer we have used additionally a HF dip to increase the adhesion between substrate and photoresist. Beside the HF dip we have used no other chemicals (like hexamethyldisilicane) to improve the adhesion between substrate and photoresist.

To create the masks and for exposure we have used “Elphy FE 1.233D” from Raith. After a short trial period we have realized some bugs in the “Elphy FE” software which made it necessary to program at least a part of the software by ourselves. The “Nanolithography” package, we have programmed as a supplement for the “Elphy FE” software includes a design part which allows to generate the masks and export them to “Elphy FE”. This solved the problem with instabilities in the mask design part of “Elphy FE”. To improve the exposure quality of periodic dot structures we have implemented a small utility which optimizes the exposure parameters.

As a part of this optimization “Nanolithography” finds the proper combination of working area, working distance and magnification based on databases which include all the technical parameters of the JSM 6400. This optimization takes also into account that the JEOL has only some discrete magnifications and working distances. Without these routines “Elphy FE” would expose either to small or to big structures.

The calibration of the scaling routines has been done with the help of a Park Scientific atomic force microscope. First we calibrated it with a gold grating of known period. After calibration we investigated a grating, which we had exposed with our electron microscope. By comparing the nominal grating period with the real period, we got a correction factor that we use now in the scaling part of the optimization.

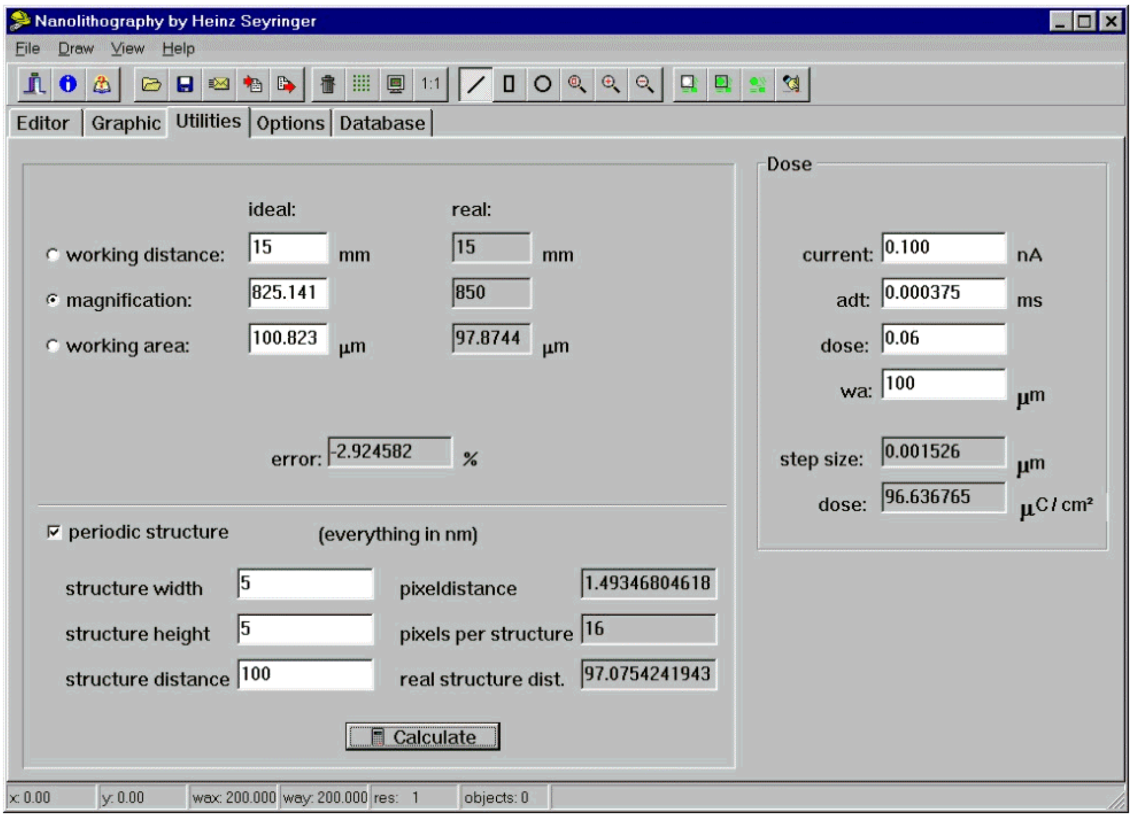

Fig. 1: Utility page of the “Nanolithography” software.

Using this setup we were able to produce holes with a diameter of less than 50 nm in an SiO_2 layer.

2. Modulation-Doped Field Effect Transistors

One of the most important applications of nanostructures is the fabrication of Schottky gates for Si/SiGe modulation-doped field-effect transistors with gate lengths below 100 nm. To align these gates properly we use the mark recognition and alignment system of “Elphy FE”. In the first step of the mark recognition we scan some big marks outside of the transistor structures to make a rough alignment of the mask coordinate system with the sample coordinate system. For the fine alignment we scan four masks in the immediate surrounding of the gate (see Fig.2). These four marks are used to correct the shift, rotation and scaling of the mask coordinate system.

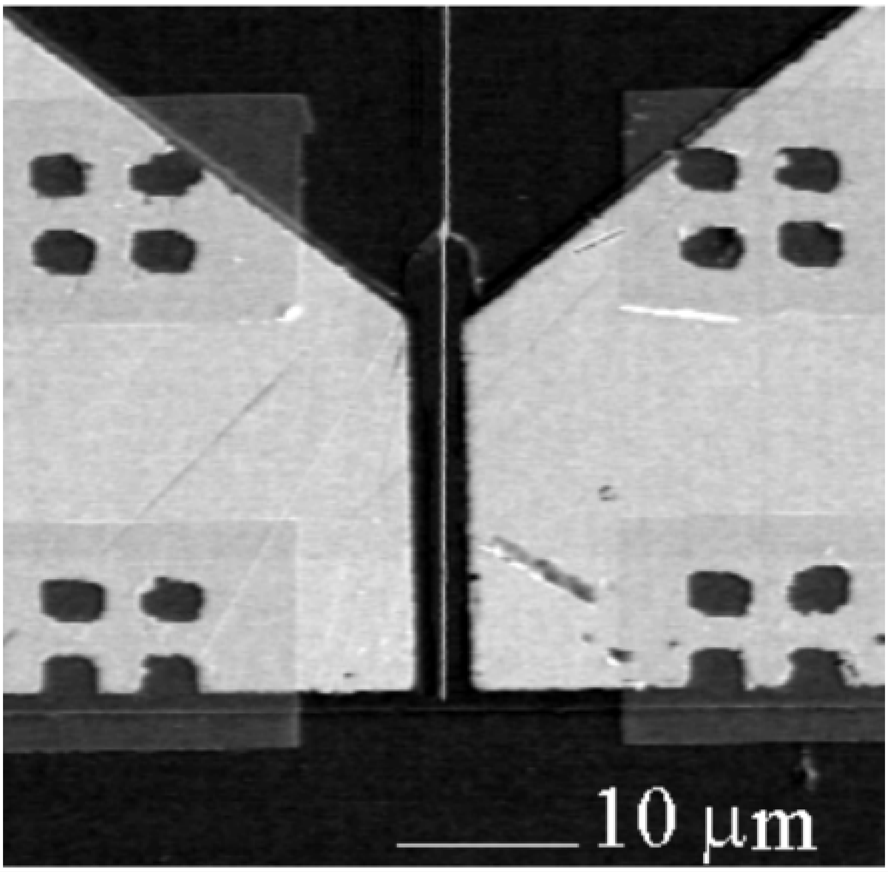

Fig. 2: Schottky gate for Si/SiGe modulation-doped field-effect transistor written by electron beam lithography.

For the lift-off technique it is very important to get negative resist flanks. The usual way to achieve this is by exposing the resist to chemicals like chlorbenzene before it is developed. This makes the top layer of the resist more resistant against developer, which causes the developer to produce slightly negative flanks. The disadvantage of this method is that the chemicals are toxic and that the chemical reaction depends on the surface morphology.

To avoid these problems we have developed a simple but efficient method to create negative flanks. We use the highest possible accelerating voltage - which is in the case of our electron microscope 40 kV - and optimize the exposure parameters for the exposure of structures with dimensions of a few nanometers. Then we expose nominally 5 nm wide gates with a dose that is much to high. A remarkable percentage of the electrons scatters from the substrate-resist interface back into the resist (because of the proximity effect) and causes a much broader exposure distribution at the interface. The result is that we get gates with gate length below 100 nm with negative flanks without any additional chemicals.

To optimize the high frequency behavior of the transistors we investigate multiple resist layers for the fabrication of gates with T- or Γ cross sections. Basically, we use PMMA 50k and PMMA 950k as the two layers. To increase the height of the gates we investigate three layer resist systems with two layers of PMMA 950k on top of a PMMA 50k layer.

3. Antidots for Magnetotransport Investigations

To produce the antidots we have used PMMA 50k and exposed arrays of boxes with side lengths of less than 70 nm. It is important for the magnetotransport investigations that all dots have the same size and shape which means that the astigmatism correction has to be done very precisely. In vacuum there are always some hydrocarbon compounds which can be used for electron beam induced chemical vapor deposition. This deposition occurs only in the region where the primary electrons hit the sample and therefore gives an image of the beam shape which allows a precise correction of the astigmatism.

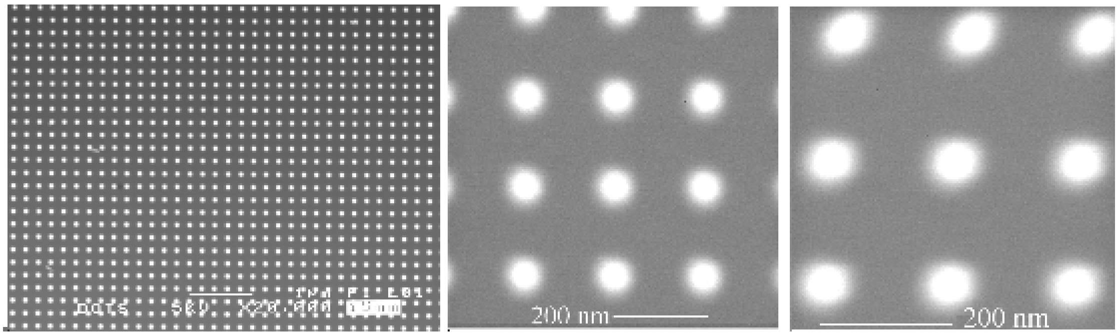

Fig. 3: Picture 3a shows a typical array of antidots. In picture 3b the astigmatism is properly corrected, while there can be seen a small astigmatism in the dots of picture 3c.

To transfer the dots from the PMMA into the silicon we use reactive ion etching (= RIE) with CF_4 gas at a power of 85 W and a pressure of 30 mtorr. The problem of the RIE is that we damage the sample and create depletion regions which have a big influence on carrier density and mobility.

By measuring the magnetoresistance we can calculate carrier density and mobility from the Shubnikov De Haas oscillations. Change in size and period of these antidots will provide information about the damaged area around the anti-dots. This information can be used to optimize the etching process and increase the electron mobility in devices by decreasing the surface scattering.

4. Oxide Windows for Ge-Dot Growth

Oxide-patterned silicon substrates are used as a template for selective molecular beam epitaxy [1]. By electron beam lithography we transferred arrays of windows less than 100 nm wide into a SiO_2 layer. These allow crystalline growth in areas where the substrate is exposed and polycrystalline deposition on the oxide covered areas. The latter can be removed selectively by etching the SiO_2 layer in diluted HF.

These oxide-windows allow the control of dot sizes and arrangements.

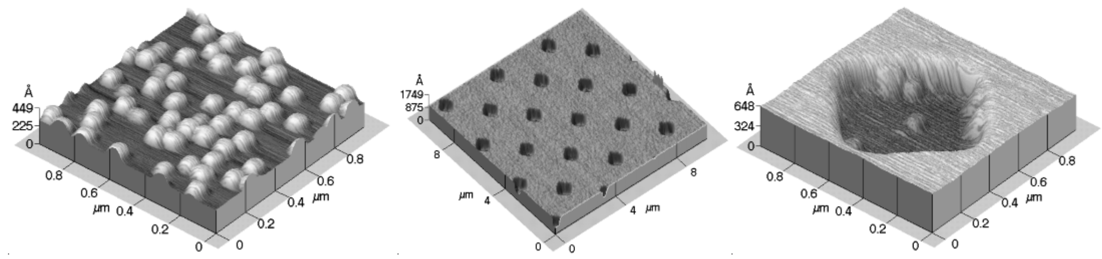

Fig. 4: Ge-dots grown on unpatterned silicon substates have a high density with a random distribution (Fig. 4.a). In contrast, oxide patterned silicon substrates (Fig. 4.b) allow us to control position and size of Ge-dots (Fig. 4.c).

5. Conclusion

With the combination of “Nanolithography 2.0” and “Elphy FE” we are able to produce nanostructures for a multitude of application. Especially the use of antidots in Hall bars for optimizing RIE damage might be of interest for industrial applications.

References

[1] E.S.Kim, N.Usami, Y.Shiraki: “Control of Ge dots in dimension and position by selective epitaxial growth and their optical properties”, *APL*, Vol. 72, 1998, pp. 1617 – 1619