Active Field Effect Transistor Fabricated by FIB-Implantation

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Focused ion beam technology has successfully proven its potential for fabrication and modification of interconnect layers. The major benefit of this approach is the fact that a photomask is redundant for microstructure generation. In this work, a focused gallium ion beam has been utilized to generate an active device. The incorporation of the ions in the substrate can be utilized for a local implantation. With this approach a field effect transistor was fabricated by implantation of Ga forming the source and drain regions. The p-channel transistor was proven to operate both in the ohmic as well as in saturation mode. This device demonstrates the versatile potential of focused ion beam processing for prototype generation.

Introduction

A FIB operated with gallium ions also allows implantation of Ga into silicon for fabrication of active devices. The high energetic ions of the FIB may also be used for implantation to obtain p-doped regions. By Ga-doping p/n-junctions in n-Si have been processed [1] – [3]. This work demonstrates the wide capabilities of direct-write deposition of materials for microelectronic prototype devices. The deposition of metallic as well as dielectric structures is shown. Using the focused ion beam the feasibility of prototyping doped regions was demonstrated by building a field effect transistor.

Experimental

High energetic 50 keV Ga^+-ions were extracted from a liquid metal ion source with an ion current tunable between 4 pA and 2 nA and could be focused down to a 10 nm effective beam diameter. A deflection system for scanning operation provided control of the focused beam for a local deposition. Semiconductor materials such as Si (100), GaAs as well as commercial microchips could be used as substrates. For fabrication of the transistor prototypes the ion beam was exclusively scanned over the source and drain regions to obtain an ultrashallow Ga implantation. The implantation dose was $6{,}5\text{x}10^{+14}$ ions/cm² at 50 keV followed by thermal activation of the doped region at 650 °C. A 200 nm thick silicon nitride acted as gate dielectric. Metallization was performed using standard lithographic techniques. The prototype transistor had a gate length of 32 µm with a channel width of 100 µm. All electrical measurements of the transistor were performed with a semiconductor analyzer controlling voltage and current of gate, drain, source and bulk.

Results

The schematic setup of the FIB-fabricated prototype field effect transistor is shown in the left image of Fig. 1 (a). By gallium implantation into n-doped Si ultrashallow p-doped source/drain regions with a thickness below 100 nm were fabricated. For the first time the fabrication of ultrathin active devices by FIB-implantation could be demonstrated.

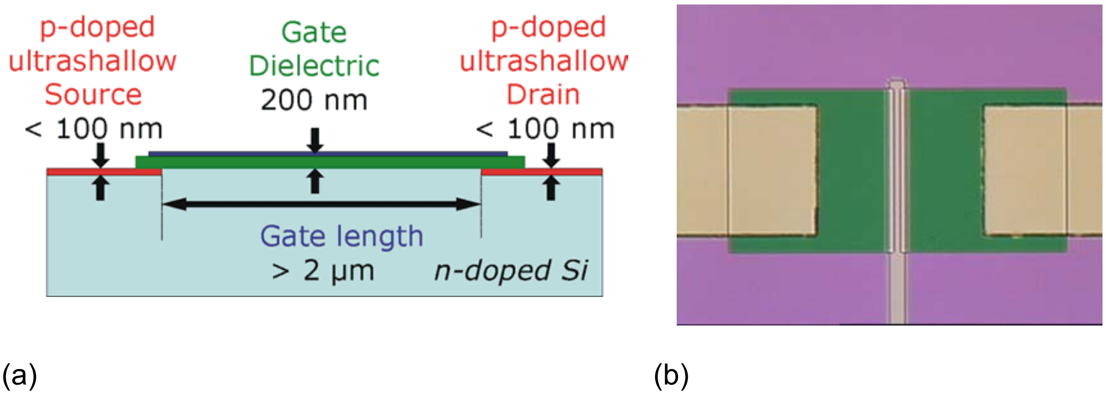

Fig. 1: Schematic illustration (a) and optical image (b) of the FET obtained by direct-write implantation of Ga.

The source and drain metal contacts to the two doped regions as well as the thin gate structure in the image center separating the doped regions are visible in the top view image of the transistor (Fig. 1 (b)). The current-voltage curves of source/bulk respectively drain/bulk measurements displayed the typical diode characteristics. The dielectric layer had negligible leakage currents in the nA range up to a –20 V gate voltage. The measurement of the output characteristics (Fig. 2) was measured for a drain voltage down to –20 V and for a gate voltage down to – 15 V. The ohmic region and the current source region can be clearly distinguished in Fig. 2. A very high threshold voltage around – 7 V was observed. It is assumed that the 200 nm thick silicon nitride deposited by plasma enhanced CVD contains trapped charges that significantly diminish the effective field in the channel region.

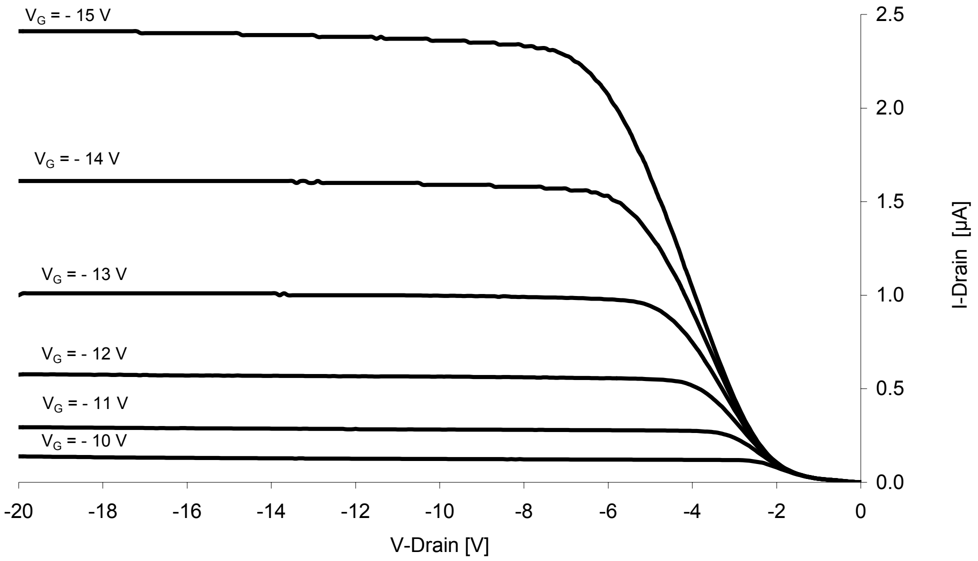

Fig. 2: Output characteristics of the FIB-processed prototype transistor

The mask-less fabrication of the p-MIS transistor providing with the full functionality as amplifier or as a switch by direct-write implantation complements the application range of direct-write deposition. Direct-write deposition and direct-write implantation allow to assess front-end and backend prototyping of silicon-based microelectronic devices.

Conclusion

Direct-write processing with a focused particle beam has been proven a powerful technique for prototype development. Using a focused beam controlled by a scan generator, arbitrary areas may be doped with gallium. This laterally confined doping supplements the potential of the FIB for direct-write deposition. The fabrication of a field effect prototype with ultrashallow source/drain regions shows the versatility of maskless direct-write technologies. This renders direct-write processing the long sought maskless method for rapid prototype development also of active microelectronic devices.

Acknowledgement

The Austrian Society for Microelectronics (GMe) is acknowledged for financial support facilitating this research. Erich Gornik is thanked for providing the clean room facility of the microstructure center of the Vienna University of Technology. John Melingailis and Lothar Frey are acknowledged for their encouragement and for constructive discussions.

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