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PECVD of poly-SiGe/Ge layers with increased total gas flow

Qiang Wang *, Andreas Göhlich, Marco Ruß, Pin Yang, Holger Vogt

Fraunhofer Institute for Microelectronic Circuits and Systems, Finkenstraße 61, 47057 Duisburg, Germany

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ABSTRACT

The PECVD of in situ boron doped SiGe and Ge layers with the increased total gas flow was investigated. It was found, that the SiGe layer could be deposited as amorphous or polycrystalline material depending on the quantity of the total gas flow, while other deposition parameters were kept constant. The increased total gas flow favors the crystallization of the deposited SiGe or Ge layers, what is attributed to the reduced gas residence time. The reduced residence time improves the crystallinity of the deposited layers by increasing the Ge content in the layers (in the case of SiGe layers) and probably additionally through the increasing of the XH_3 radicals in the plasma. With the deposition method with increased total gas flow, poly-SiGe and poly-Ge layers with very low resistivity (about 1 mΩ-cm) can be deposited at very low substrate temperatures (poly-SiGe: ⩽375 °C; poly-Ge: ⩽340 °C). These layers have small tensile stresses.

1. Introduction

Because of its low deposition temperature and high deposition rate, the plasma-enhanced chemical vapor deposition (PECVD) of polycrystalline silicon–germanium (SiGe) becomes a very attractive method for the fabrication of structural layers of microelectromechanical systems (MEMS) in the post-CMOS integration process. With the monolithic integration of MEMS structures and the electronics, sensors and actuators with smaller dimensions, better stability and more functions can be realized. The mechanical properties of poly-SiGe are comparable to those of poly-Si [1], and the latter is a classical material for the fabrication of MEMS structures. While the poly-Si has to be deposited with high temperatures, poly-SiGe can be deposited at low temperatures below the thermal budget required by the CMOS electronics. Another advantage of the poly-SiGe material is the fact, that in situ doped poly-SiGe is electrically conductive, and there is no need to perform additional ion implantations and activations or other high temperature doping processes.

Nowadays, there are mainly two approaches to obtain PECVD SiGe layers with low resistivity at CMOS-compatible substrate temperatures (⩽450 °C). One is with hydrogen dilution, and the other one is with a predeposited CVD seed layer [2,3]. Although with the former approach microcrystalline SiGe films can be achieved at very low substrate temperatures (<400 °C), the deposition rate of this approach (typically 20 nm/min) is strongly constrained by the hydrogen dilution [4]. Furthermore, the resistivity of the so produced films (typically >10 mΩcm) is not low enough for some applications. In the latter approach, a layer stack consisting of amorphous SiGe (or amorphous Si), CVD SiGe and PECVD SiGe is deposited. The amorphous SiGe (a-SiGe) layer guarantees the adhesion of the subsequently deposited CVD SiGe layer on the wafer and avoids the long incubation time of the CVD. The polycrystalline CVD layer serves as a seed layer for the following PECVD SiGe layer, which can be deposited as a polycrystalline layer at circa 450 °C. This approach is relative complicated and the average deposition rate is limited by the CVD deposition, if a structural layer thinner than 1 μm should be achieved. Furthermore, in this approach the deposition temperature cannot be set below 450 °C to obtain a poly-SiGe layer with low resistivity (<1 mΩ-cm).

In our study, it was observed, that the silicon to germanium ratio and the crystallinity of the in situ boron doped PECVD SiGe films are dependent on the total gas flow. On the basis of this phenomenon, the deposition method with increased total gas flow was developed and applied for the fabrication of pressure sensor test structures with SiGe and Ge membranes.

2. Experimental procedure

In this work, in situ boron-doped PECVD SiGe and Ge layers were deposited with different total gas flows at different substrate

Abbreviations: PECVD, plasma-enhanced chemical vapor deposition; NTGF, normalised total gas flow, defined as NTGF = (total gas flow)/(1364 sccm).

* Corresponding author. Tel.: +49 203 3783 267; fax: +49 203 3783 266.
E-mail address: Qiang.Wang@ims.fraunhofer.de (Q. Wang).

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temperatures, while all the other parameters were kept constant. The depositions were carried out with a Precision 5000 cold wall CVD-system from Applied Materials. The rf frequency for the PECVD depositions was 13.56 MHz. Pure monosilane (SiH_4) and pure monogermane (GeH_4) were used respectively as the silicon and the germanium source. For the in situ boron-doping, 5% diborane (B_2H_6) in argon was employed. These process gases were diluted with argon during deposition. The ratio of the gas flow rates for the different, namely GeH_4, SiH_4, Ar and B_2H_6 was 208:150:2365:5 for the deposition of the SiGe layers and that for the deposition of the Ge layers was 208:2361:5, respectively for GeH_4, Ar and B_2H_6. In this paper the total gas flow is normalised with 1364 sccm to be presented more clearly. A parameter NTGF is defined as NTGF = (total gas flow)/(1364 sccm). The electrical power at the deposition was 66 W and the pressure in the process chamber during the process was 2 Torr. The layers were deposited on 8-inch (1 0 0) silicon wafers with a thin PECVD SiO_2 layer on top.

The sheet resistance of the deposited films was measured with a CDE ResMap system at 9 points over the wafer. Transmission electron microscopy (TEM) analysis was carried out to verify the crystallinity of the film. The Si and Ge concentration in the SiGe films were examined with the energy-dispersive X-ray spectroscopy (EDX). The average stress of deposited films was determined using a wafer geometry gauge (MX 208) from Eichhorn & Hausmann. X-ray diffraction Analysis was carried out to study the crystallinity and the Si to Ge ratio of the layers, using a PANalytical X'Pert diffractometer, which utilized an X-ray source with a wavelength of 1.54056 Å.

3. Characterization of the SiGe layers deposited with different total gas flows

SiGe layers were deposited with different NTGFs at the substrate temperature of circa 365 °C, 370 °C and 375 °C, while other parameters were kept constant. The resistivity of the layers at different NTGFs is presented in Fig. 1. The resistivity decreases, while the total gas flow increases. The XRD and TEM analysis in the later part of this paper will demonstrate, that the resistivity reflects the degree of crystallization of the layers and a smaller resistivity indicates a better crystallinity. The characterization of the crystallization of the SiGe layers with the resistivity is a common approach in the research of the SiGe deposition [2,5,6]. Fig. 1 shows that the deposited SiGe layers can be brought from amorphous to crystalline state, only by increasing the total gas flow.

The crystallization degree of one of the layers, whose resistivity values are presented in Fig. 1, is analyzed with TEM. This layer was deposited at the substrate temperature of 370 °C with NTGF = 2.0. A bright field and a dark field image of the TEM analysis are shown together in Fig. 2. Many large conical crystals can be observed in the SiGe layer. The layer grows at the very beginning as an amorphous material and after circa 50 nm the conical crystals begin to grow from small nuclei.

The Ge-concentration in the SiGe layers, which were deposited at the substrate temperature of 365 °C and 370 °C, were measured with EDX. Fig. 3 shows the results of the measurements. The Ge-concentration rises with the increasing total gas flow and goes into saturation at NTGF ≈ 2.0. Later discussions in this paper show that this phenomenon is probably caused by the changed gas residence time in the process chamber. The gas residence time will be reduced, if the total gas flow increases [7].

The stress of the SiGe layers, which were deposited at the substrate temperature of 370 °C, is displayed in Fig. 4 as a function of the total gas flow. These SiGe layers have tensile stresses and the stress declines, as the total gas flow rises. While the stress for NTGF = 0.5 is 180 MPa, it decreases to about 30 MPa at NTGF = 2.1. Together with the characterization of the resistivity of the layers (Fig. 1), it is seen that the lowest resistivity and the smallest stress occur simultaneously at the maximal total gas flow. Such a combination of a low resistivity and a small stress is desirable in many MEMS applications.

Fig 5 shows the deposition rate of the SiGe layers deposited at substrate temperatures of 365 °C, 370 °C and 375 °C. It can be seen that the deposition rate increases with the increasing total gas flow. The deposition rate for NTGF = 2.1 is about 100 nm/min higher than that for NTGF = 0.5. The substrate temperature has hardly any effect on the deposition rate. The fact that the deposition rate increases with the increase of the total gas flow and does not depend on the substrate temperature, indicates that the growth of the layer is limited by the delivery of the layer-forming particles, but not by the surface reactions of the growing film.

4. Characterization of the Ge layers deposited with different total gas flows

The deposition of the in situ boron-doped Ge-layers was carried out at substrate temperatures of circa 330 °C and 340 °C. Just like the deposition of the SiGe layers, the Ge layers were also deposited with different total gas flows, while other parameters such as

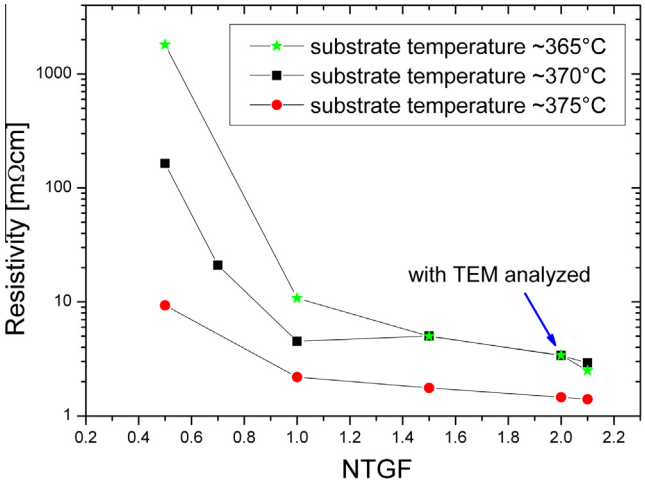

Fig. 1. Resistivity of the deposited SiGe layers as a function of NTGF (The uncertainty of the resistivity values is about ±3.5%).

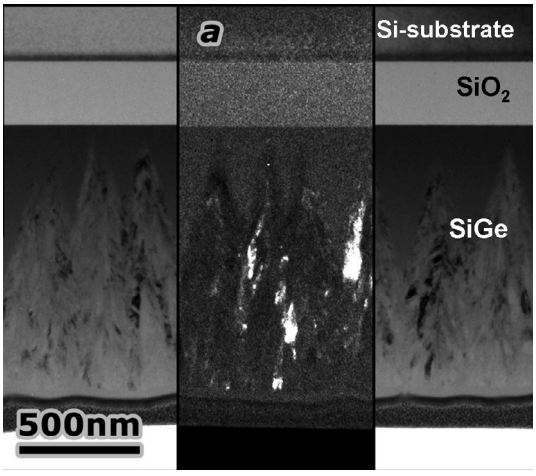

Fig. 2. Bright field and dark field (a) TEM image of the SiGe layer, which was deposited at the substrate temperature of circa 370 °C with NTGF = 2.0.