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On low-frequency noise of polycrystalline Ge_xSi_{1-x} for sub-micron CMOS technologies

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Abstract

Polycrystalline gate films of Ge_xSi_{1-x} were deposited using low pressure chemical vapor deposition. To study the effects of different Ge contents on the noise properties, a value $x = 0$, 0.3, and 0.6 was selected. Samples of 300 and 500 nm thickness were prepared for comparing the thickness effects on the quality of the gate films. The gate films were implanted with different concentrations of boron. The morphology and electrical properties have been characterized using atomic force microscopy, transmission electron microscopy, and Hall-effect measurements. Conductance fluctuations were measured at room temperature. We present here how low-frequency noise depends on the Ge contents, the doping concentration, and on the thickness of the gate film. The $1/f$ noise in polycrystalline Ge_xSi_{1-x} can be analyzed in terms of mobility fluctuations caused by lattice scattering. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

In the past decade, serious efforts have been made to combine the best of Silicon and Germanium by using GeSi alloys in devices. This led to a new GeSi technology that is of great interest for microelectronics. The poly-Ge_xSi_{1-x} technology makes it possible, (i) to offer a mid-gap gate material that is compatible with standard Si technology, (ii) to respond to technically emerging challenges as the dimensions of semiconductor devices are continuously scaled down into the deep sub-micron regime. The threshold voltage V_t of metal oxide semiconductor field effect transistors (MOSFETs) is limited by the off-current requirement. Downscaling requires increasing the doping concentration, which reduces the mobility and hence the device speed. This issue can be addressed by bandgap engineering. The change of the gate-to-bulk work-function by using SiGe as a gate material can give the same V_t as for poly-Si gate material while keeping the doping level lower thereby enhancing the channel mobility and saturation current. A midgap-work-function gate is also symmetrical for n-type and p-type MOSFETs. By varying the Ge fraction, the workfunction of poly-Ge_xSi_{1-x} can be manipulated by 200–300 mV towards midgap. Technology issues, such as compatibility of gate material with thin gate oxide, with Si processing, and deposition of the poly-Ge_xSi_{1-x} gate film with good electrical properties, have been extensively investigated in the last decade. However, the noise properties of poly-Ge_xSi_{1-x} were much less studied. The technological importance of polycrystalline Ge_xSi_{1-x} has increased to the point where knowledge of noise properties is of value to the design and process engineer. For example, in microwave (telecom) and mixed mode analog–digital circuits, the low-frequency noise from transistors and resistors in the circuits affect, either directly, e.g. the design of low-noise amplifiers, or indirectly, by determining the phase noise of high-frequency oscillators and mixers. The conduction noise in the gate film of a MOSFET is known to have little effect on the noise in the drain current. However, in integrated circuits in which poly-Ge_xSi_{1-x} gated MOSFETs are used, poly-Ge_xSi_{1-x} resistors will also be included. Noise characterization of these layers may therefore be important. In

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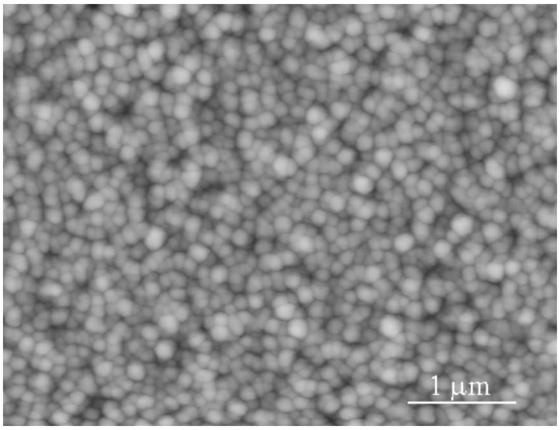
addition, a noisy poly-Ge_xSi_{1-x} gate film may point to poor material quality. The boron diffusion through the low-quality gate film down to the oxide layer can degrade the quality of the oxide layer. This will result in distributed space charges and defects in the oxide layer, and thus, a high noise level in the drain current. Here, we study low-frequency noise in polycrystalline Ge_xSi_{1-x} film grown by low-pressure chemical vapor deposition (LPCVD). The results will be presented in terms of Ge contents, doping concentration and film thickness. Our results support the notion that mobility fluctuations are the origin of $1/f$ noise in polycrystalline materials.

2. Characteristics of the gate films

The gate films were deposited by LPCVD on thermal-oxide-covered (25 nm) n-type Si wafers. Silane (SiH_4) and germane (GeH_4) were used as source materials in the LPCVD process. This process was optimized with respect to the texture and morphology of the poly-GeSi layer. Detailed information of the growth can be found in Ref. [1]. To study the effects of material composition different Ge fractions were selected: $x = 0$, 0.3, and 0.6. It is widely believed that the compatibility with Si technology reduces for Ge fractions larger than 0.6. It is typical that the electrical properties of poly-GeSi film are very sensitive to the morphology of the film which varies with film thickness. Therefore, samples of 300 and 500 nm thickness were prepared for comparison. The 300-nm-thick samples were implanted with 40 keV BF_2^+ ions, and then annealed in two steps for a total of 30 min at 850°C. First the samples were annealed in an O_2 ambient for 5 min to form a thin oxide layer to prevent out-diffusion of the dopants and then in an N_2 ambient for 25 min. The 500-nm-thick samples were implanted with 70 keV BF_2^+ ions, and annealed at 800°C for 60 min. The annealing ensures a homogeneous doping distribution throughout the film. Fig. 1 shows a typical microphotograph of our samples with a homogenous distribution of vertical columned structures. Such a structure is the best one for the gate of CMOS devices. The average column diameter, which is weakly dependent on the doping level, is about 170 ± 55 nm. Table 1 lists the pertinent details of the samples we used.

(a)



(b)

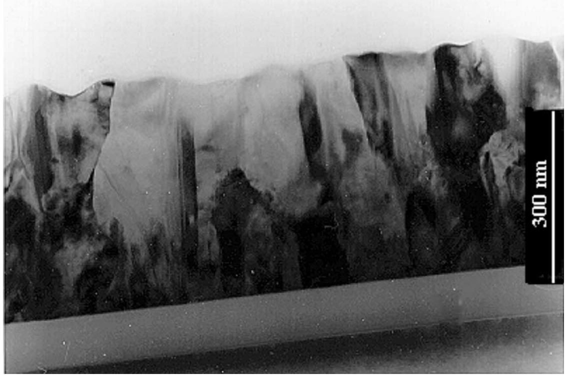


Fig. 1. (a) Transmission electron microscopy picture of the cross-section and (b) atomic force microscopy picture of the surface.

Table 1
Sample specifications

Sample code	Ge fraction (%)	N_A (cm^{-3})	Ion beam (keV)	Thickness (nm)
30T500	30	10^{18}–10^{20}	70	500
30T300	30	10^{18}–10^{20}	40	300
60T300	60	10^{18}–10^{20}	40	300
00T500	0	10^{18}–10^{20}	70	500

The samples were lithographically defined as two crossing bars (Fig. 2). Each of the bars has a length of 3 mm and a width of 0.5 mm. Measurements of the Hall effect yielded a Hall concentration of 0.7 times the doping concentration and mobility values varying from 11 to 33 $cm^2/V\,s$. In our calculation the Hall scattering factor of mono-Si was used because alloy scattering in Ge_xSi_{1-x} is negligible [2]. To analyze the effects of the grain-boundaries on the transport of carriers in the poly-GeSi, we list in Table 2 the hole mobility in doped mono-crystalline and poly-crystalline GeSi, and the hole mobility limited by lattice scattering only. We see that in mono-crystalline GeSi the mobility is about 80 $cm^2/V\,s$ at a doping level of $10^{19} cm^{-3}$, while at this doping level the mobility of poly-GeSi is only about 18 $cm^2/V\,s$. Therefore in our samples the grain boundaries strongly limit the charge transport.

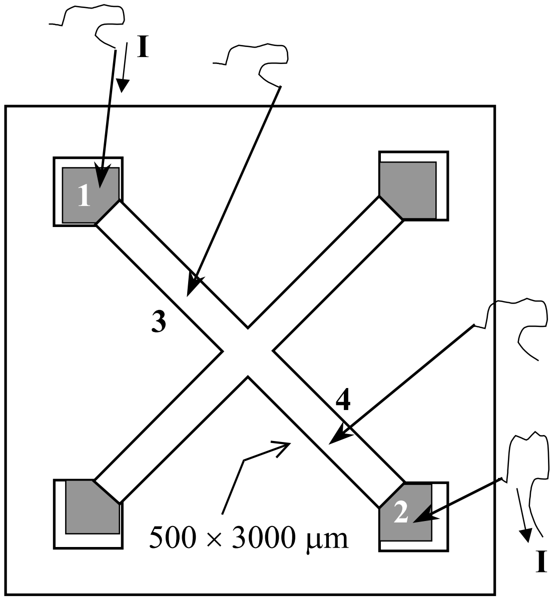


Fig. 2. Sample structure and probing configuration. 1 and 2 are current contacts, 3 and 4 are noise measurement contacts.

Table 2
Mobilities in the samples

Sample	N_A (cm^{-3})	μ_H (cm^2/V s)
Poly-SiGe [1]	1×10^{19}	18.1
Mono-SiGe [3]	1×10^{19}	84
Lattice scattering in SiGe [3]		260

3. Low-frequency noise measurement and results

We used a femto–ampere DC level triaxial probe system together with an HP semiconductor parameter analyzer 4155A to make *I–V* measurements. In addition to probing the contacts of the gate film, we connected a probe to the triaxial chuck surface. Measurements of current through this probe revealed a significant leakage from the gate film to the substrate in some of samples. Therefore, as a first step samples without this type of gate leakage were selected from the wafers for noise measurements. Those selected samples have a linear *I–V* characteristic over the voltage region from −7 to +7 V. We measured voltage fluctuations using the four-point method as shown in Fig. 2. The current passed through one pair of contacts while the noise voltage is measured with another pair of contacts.

Most noise measurements revealed pure $1/f$ spectra. Only sample 30T300 doped at 10^{19} cm^{-3} exhibited components associated with generation–recombination (g–r) noise in addition to $1/f$ noise. Typical noise power spectra are presented in Fig. 3. Even though some minor g–r contributions may be present (most pronounced at 50 mV) good estimates for the upper limit of the $1/f$-noise magnitude can be extracted. The noise power spectral density scales with the voltage squared for all samples. The largest operating voltage, 95 mV, corresponds to a current density of 8.5 A/cm^2.

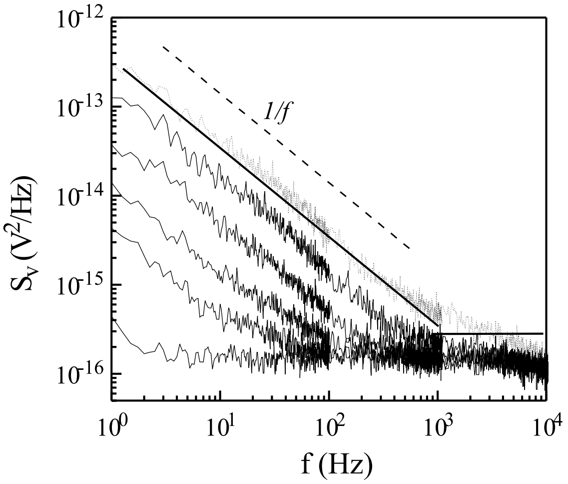


Fig. 3. Noise power spectral density measured from 60T300 doped at 10^{19} cm^{-3}. From top to bottom, the bias voltage is: 95, 50, 25, 12, 6.3, and 0 mV. The dashed-line is for guiding the eyes. The solid-lines are the $1/f$ noise and the thermal noise components.

To compare the noise level in different samples, we express the $1/f$ noise by the empirical Hooge relation [4].

$$\frac{S_V}{V^2} = \frac{S_R}{R^2} = \frac{S_G}{G^2} = \frac{\alpha}{fN_H}, \tag{1}$$

where V is the voltage, R the resistance and G the conductance, S_X is the noise power density of the quantity X, α the noise parameter, f the frequency and N_H the total number of carriers in the volume involved in the noise generation. This relation was proposed to quantify the $1/f$ noise in homogeneous samples. In the situation where the noise generators are not homogeneously distributed, N_H is an effective number of carriers. Neglecting the complications of inhomogeneity associated with the granular morphology, we calculate α using as-measured Hall concentrations. We have to stress that this α does not have the meaning originally proposed in Ref. [4]. The analysis of the origin of the noise in any polycrystalline material cannot be carried out using the value of this α only. Nevertheless, such an α is a good measure of the relative magnitude of the noise in different gate films.

The dependence of the noise on Ge content and boron doping concentration has been obtained. The noise parameter α of the gate films is depicted in Fig. 4.

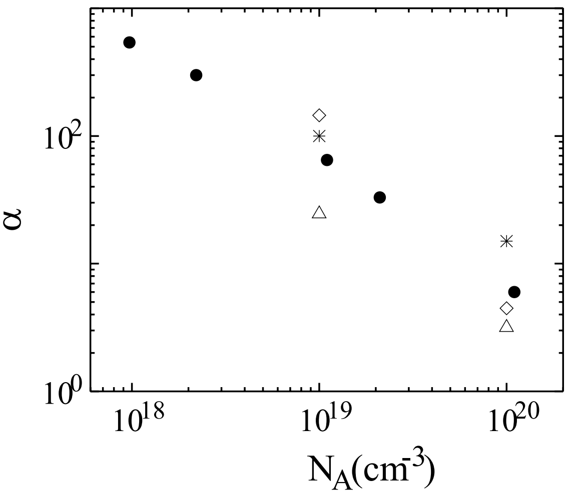


Fig. 4. Noise parameter α vs. doping concentration. (∗) 00T500, (Δ) 30T300, (•) 30T500, (◇) 60T300.

We found that decreasing boundary scattering at higher doping concentration results in increased mobility, and decreased $1/f$ noise parameter α. It is clear that the noise properties of poly-GeSi are comparable with that of poly-Si. At a very high doping level ($\sim 10^{20}$ cm^{-3}), the poly-GeSi gate film with 60% of Ge does not appear to be very noisy when compared with the 30% Ge film. However, at a doping level of $\sim 10^{19}$ cm^{-3} the poly-GeSi film with 60% of Ge is quite noisy. The noise levels of thicker gate films doped with higher energy ion beam are slightly higher than the noise levels in thinner gate films doped with lower energy ion beam. This may be related to better homogeneity of the thinner gate films. In addition, the thinner films are implanted at lower energies, reducing the amount of incurred lattice damage.

4. Discussion

The gate leakage results from the processing related damage/degradation of the 25-nm-oxide layer under the gate films. The noise measured from those samples would not give any information on the noise in poly-Ge_xSi_{1-x} gate films. First, trapping–detrapping of holes in the gate film via defects in the damaged/degraded oxide layer results in g–r noise components or/and $1/f$ shaped contributions that add to the $1/f$ spectrum of the gate films, masking the fundamental $1/f$ noise. Second, the leakage path can form a parallel conducting channel in the substrate. From the noise measurements it is not possible to differentiate between contributions from the gate film and those from the parallel substrate channel. We observed that the noise in 'leaky' devices is at least one order of magnitude higher than that in 'good' devices. One cannot extract the $1/f$ noise of the gate films in these cases. In sample 30T300 the observation of high g–r bumps is evidence of the imperfection of the oxide layer.

Regarding the origin of the $1/f$ noise in polycrystalline materials, there are two competing models, similar to crystalline materials, namely the number fluctuations and the mobility fluctuations. Few investigations of noise in polysilicon can be found in the literature [5–9]. De Graaff and Huybers [5], Jang [6], and Luo and Bosman [7] reported on the $1/f$ noise of polysilicon. All three papers [5–7] stated that the measured noise is caused by mobility fluctuations, although there were some disagreements. Luo and Bosman made corrections to the older model and proposed a more mature model.

Madenach and Werner [8] and Dimitriadis et al. [9] presented an analysis in support of a typical number-fluctuation model. Especially, Dimitriadis et al. proposed that the origin of the noise in intrinsic polysilicon is related to fluctuations in the free carrier density due to trapping–detrapping via gap states. They assumed two types of trapping states: mid-gap states with a uniform energy distribution and gap states in the exponential band tails. Such a distribution of trap states has never been experimentally verified. The model also cannot explain the doping dependence of the noise that we observed in Fig. 4. Of course their model was applied to intrinsic samples, whereas ours are (heavily) doped.

More recently we presented a detailed analysis of the $1/f$ noise in poly-GeSi gate films to distinguish between the $1/f$ noise from grain-boundaries, depletion region, and neutral region of the grains [1]. It was concluded that the $1/f$ noise is generated in the depletion region of the grains. Inside the grains we can apply the lattice scattering model [4] for the $1/f$ noise because the grains themselves are crystalline. As a result we have

$$\alpha_g = \left(\frac{\mu_g}{\mu_{Latt}}\right)^2 \alpha_{Latt}, \tag{2}$$

where α_g is the Hooge parameter for the crystal grains in the poly-GeSi film and Mg is the mobility in the crystal grain. α_{Latt} is a material constant characterizing the $1/f$ noise due only to the lattice scattering. Thus, α_{Latt} has the same value in the depletion region (at the grain boundary) and neutral region of the crystal grain.

Based on Eq. (2), we derived the following relation between the measured α and the doping concentration n_A (for detail, see the derivation of Eq. (22) in Ref. [1]),

$$\alpha \propto n_A^{-\lambda}, \tag{3}$$

where λ varies from 0.7 to 0.8. Our experimental results in Fig. 4 show that λ is in this predicted range and independent of the Ge content. Therefore, the noise measurements on samples with different Ge contents, different doping concentrations, and different thicknesses support the mobility fluctuation model.

5. Conclusions

The noise properties of poly-Ge$_x$Si$_{1-x}$ are comparable with that of poly-Si. The noise in the poly-Ge$_x$Si$_{1-x}$ gate films is independent of the Ge mole fraction for $0 \leqslant x \leqslant 0.6$. The thickness of the gate film has only a minor effect on the noise magnitude: the thinner samples are slightly more quiet. We found that decreasing boundary scattering at higher doping concentration results in increased mobility, and decreased $1/f$ noise parameter α. The origin of the noise is the mobility fluctuations.

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