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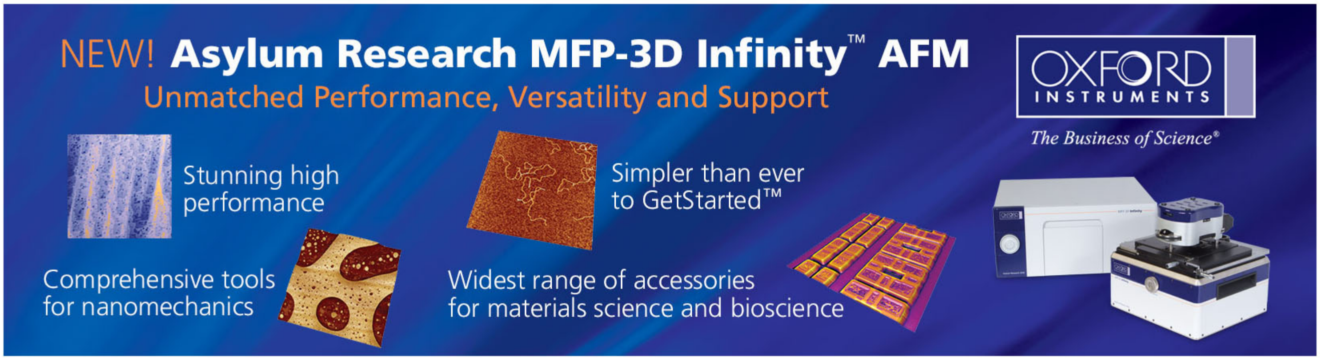
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Analysis of low-frequency noise in boron-doped polycrystalline silicon–germanium resistors

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Low-frequency noise in boron-doped polycrystalline silicon–germanium (poly-$Si_{1-x}Ge_x$) resistors at various temperatures is studied. The poly-$Si_{1-x}Ge_x$ films with 0%∼36% Ge content were grown using ultrahigh vacuum chemical molecular epitaxy system. We find that the low-frequency noise in poly-$Si_{1-x}Ge_x$ decreases with increasing Ge content, due to the lower potential barrier height of grain boundaries in higher Ge content samples. Moreover, the low-frequency noise decreases with increasing temperature. These results are well explained by the carrier mobility fluctuation model.

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In analog and radio frequency circuits, polycrystalline silicon (poly-Si) films are frequently used for resistors, the gate material of metal-oxide-semiconductor field-effect transistors, and the emitter contacts of bipolar junction transistors. Recently, polycrystalline silicon–germanium (poly-$Si_{1-x}Ge_x$) has been shown to be an attractive alternative to conventional poly-Si material for various integrated circuit applications.[1–3] By taking advantage of its lower processing temperature, thin film transistors can be fabricated with poly-$Si_{1-x}Ge_x$ films with processing temperature not exceeding 550 °C.[1] Furthermore, compatibility with existing silicon processing technology and the ability to adjust the threshold voltage by changing the Ge content have made heavily doped p-type poly-$Si_{1-x}Ge_x$ a very promising gate-electrode material for deep submicrometer complementary metal-oxide-semiconductor technologies.[2,3] Because the low-frequency noise in transistors and resistors may contribute to the phase noise of the radio frequency circuits or systems, it is important to predict the amount of noise in them. Several researchers have studied the noise properties of poly-Si films.[4–7] Both carrier number fluctuations,[5] and mobility fluctuations[6,7] were supported for the possible mechanisms which can cause the low-frequency noise. However, the low-frequency noise in poly-$Si_{1-x}Ge_x$ resistor was less studied.[8,9] In this letter, the low-frequency noise in boron-doped poly-$Si_{1-x}Ge_x$ resistors at various temperatures is investigated. The relationship of noise and Ge content in poly-$Si_{1-x}Ge_x$ resistors can be well predicted using the mobility fluctuation model.

In this work, poly-$Si_{1-x}Ge_x$ films were grown by ultrahigh vacuum chemical molecular epitaxy system to a thickness of ∼0.2 μm at 580 °C onto thermally grown silicon nitride. Pure disilane and germane were used as the source gases. The Ge content x in polycrystalline film was varied from 0 to 0.36. Boron atoms were implanted into the films by BF_2^+ at an energy of 20 keV. After the ion implantation, furnace annealing at 800 °C for 20 min and rapid thermal annealing at 1050 °C for 10 s were performed for dopant activation and uniform doping distribution. Kelvin resistor structures were fabricated and used to accurately measure resistivity. The dimension of all samples studied was $500\times 10\ \mu m^2$. Current–voltage characteristics of these poly-$Si_{1-x}Ge_x$ resistors were measured using an HP4156A semiconductor parameter analyzer. The noise measurements were performed at various temperatures using a BTA9812B noise analyzer in conjunction with an HP35670A dynamic signal analyzer.

Figure 1 shows a typical result of the measured spectral density of the current noise in a poly-$Si_{1-x}Ge_x$ resistor at room temperature for various applied currents. The spectra reveal the presence of a large pure $1/f$ excess noise signal. As can be seen in Fig. 1, the noise decreases approximately inversely proportional to frequency. The exponent of the frequency slope of the noise varied between -0.95 and -1,

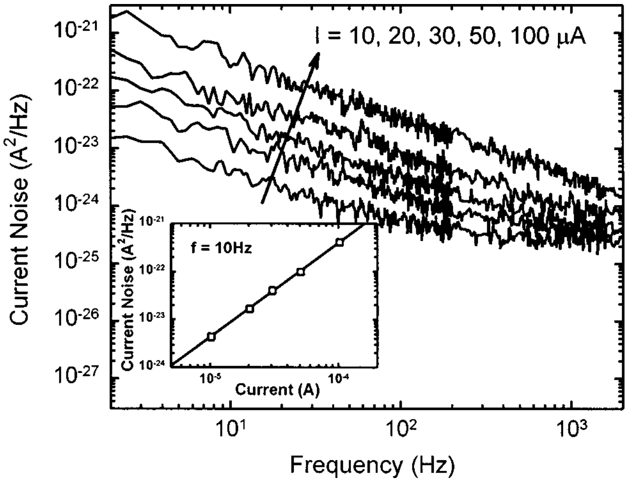

FIG. 1. Current noise spectrum vs frequency of a moderately doped ($B=6\times 10^{18}\ cm^{-3}$) poly-$Si_{0.64}Ge_{0.36}$ resistor. Inset shows the current noise as a function of applied current at $f=10$ Hz.

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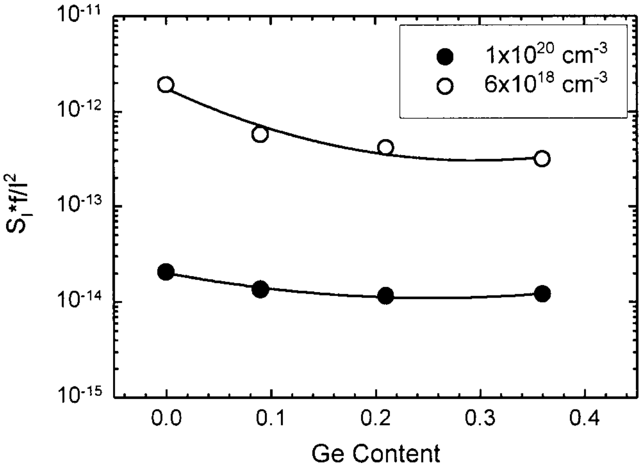

FIG. 2. Normalized current noise as a function of Ge content at different boron doping levels.

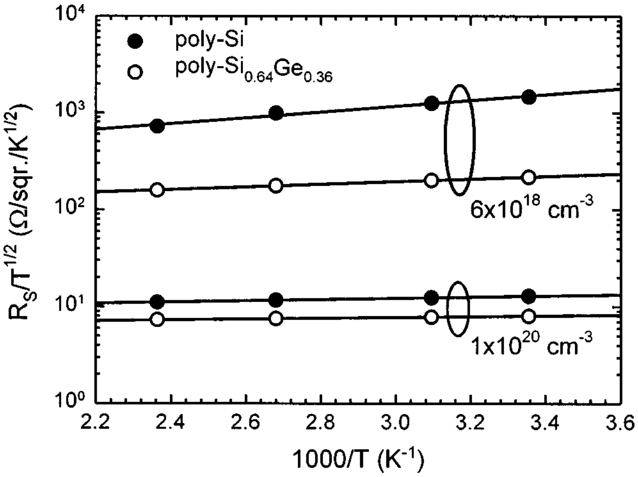

FIG. 3. Normalized sheet resistance of poly-Si and poly-Si$_{0.64}$Ge$_{0.36}$ for two boron concentrations at different temperatures.

slightly increasing toward higher applied currents. Moreover, the variation of noise intensity varied as the square of current, as shown in the inset of Fig. 1. From these observations, the current noise can be normalized with frequency and the square of the current to permit a clear comparison of resistors with different Ge content. Figure 2 shows the normalized current noise in poly-Si$_{1-x}$Ge$_x$ resistors as a function of the Ge content. The low-frequency noise is almost independent of Ge content in heavily doped ($B = 1\times10^{20}$ cm^{-3}) poly-Si$_{1-x}$Ge$_x$ resistors. However, the noise decreases with increasing Ge content in moderately doped samples ($B=6\times10^{18}$ cm^{-3}). As seen in Fig. 2, the poly-Si$_{0.64}$Ge$_{0.36}$ exhibits a significantly lower noise level than the poly-Si, making poly-Si$_{1-x}$Ge$_x$ films the preferred choice for analog resistors.

In the generally accepted model of poly-Si, the material is viewed as composed of small crystallites joined together by grain boundaries.[10,11] Inside each crystallite, the atoms are arranged in a periodic manner forming small single crystals, while the grain boundaries are composed of disordered atoms and contain large numbers of defects due to incomplete bonding. From the literature, the grain boundaries contain trapping states that are capable of trapping mobile carriers and contributing to the creation of space-charge potential barriers.[12] The potential barriers will block the transport of free carriers between the grains, thereby reducing the apparent carrier mobility.[12] For low and moderately doped poly-Si, the sheet resistance R_s can be expressed as[13]

$$R_S = \text{const.}\sqrt{T}\exp\left(\frac{q\phi_B}{kT}\right), \tag{1}$$

where T is the temperature, ϕ_{B} is the potential barrier height, and k is Boltzmann's constant. To determine the barrier heights of the grain boundaries, the sheet resistance has been determined as a function of the measurement temperature for poly-Si and poly-Si$_{0.64}$Ge$_{0.36}$ samples. In Fig. 3, the logarithm of the normalized sheet resistance is plotted as a function of reciprocal temperature. For heavily doped samples, the sheet resistance contains barrier and bulk grain components, so the bulk resistance must be subtracted from Eq. (1). The obtained values for ϕ_{B} are listed in Table I. It is shown that the barrier height is lower for the Si$_{1-x}$Ge$_{1-x}$ samples compared to the Si samples at equal doping levels. In the case of poly-Si, both p- and n-type doped material will show a similar trapping behavior. In the case of poly-Ge, the traps at the grain boundaries are p type, and the energy levels of the traps shift toward the valence band. Hence, Si$_{1-x}$Ge$_x$ has a lower potential barrier for the boron-doped samples.[14] It is believed that the observed $1/f$ noise in poly-Si is attributed to carrier mobility fluctuations occurring in the space charge regions near the grain boundary. From the model proposed by Luo, the normalized current noise can be expressed as[7]

$$\frac{S_I\times f}{I^2} = \frac{1}{N_{\mathrm{eff}}}\left(\frac{v_r}{v_d}\right)^2\frac{q^2 d\alpha}{3\varepsilon kTA}\exp\left(\frac{q\phi_B}{kT}\right), \tag{2}$$

where S_I is the measured current noise spectral density, I is the bias current, f is the frequency, N_{eff} is the effective number of large-barrier grains in the conduction path, v_r is the recombination velocity, v_d is the diffusion velocity, ε is the dielectric constant, A is the cross section of the resistor, d is the width of a one-sided space charge region, and α is the noise parameter for the grains. Substituting $d = (2\varepsilon\phi_{\mathrm{B}}/qn)^{1/2}$ in Eq. (2), we have

$$\frac{S_I\times f}{I^2} \propto \sqrt{\phi_B}\exp\left(\frac{q\phi_B}{kT}\right), \tag{3}$$

Hence, the noise will depend on the barrier height according to Eq. (3). For moderately doped samples, the difference in the barrier height can lead to a factor of 6 difference in noise between Si and Si$_{0.64}$Ge$_{0.36}$. For both materials, the potential barriers are lower with increasing dopant concentration and the relative difference becomes smaller, so that the effect of the potential barriers becomes less important. For heavily doped samples, the potential barrier height only contributes approximately a factor 1.5 to the difference in noise.

TABLE I. Grain boundary energy barriers of boron-doped poly-Si and poly-Si$_{0.64}$Ge$_{0.36}$ samples for two boron concentrations.

	$q\phi_{\mathrm{B}}$ (meV)	
Sample	B 6×10^{18} cm^{-3}	B 1×10^{20} cm^{-3}
Poly-Si	61	14
Poly-SiGe	27	9

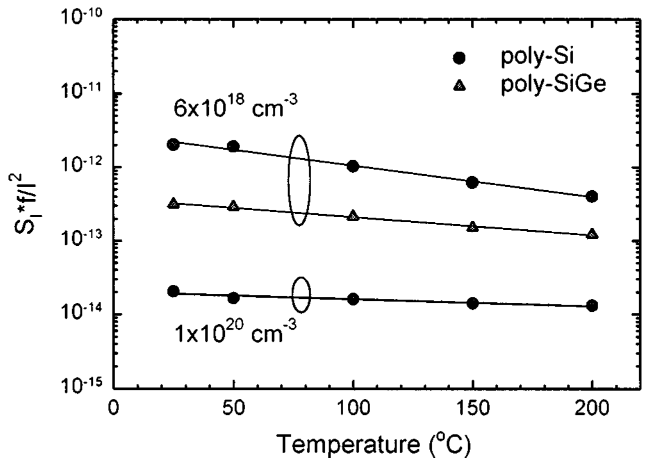

FIG. 4. Normalized current noise as a function of temperature for poly-Si and poly-$Si_{0.64}Ge_{0.36}$ resistors at different boron doping level.

The temperature dependence of the low-frequency noise in poly-$Si_{1-x}Ge_x$ resistors was also measured. The normalized spectral noise density for the poly-$Si_{1-x}Ge_x$ resistors over the temperature range from room temperature to 200 °C is shown in Fig. 4. It is seen that the low-frequency noise decreases with increasing temperature. For resistors with higher grain boundary potential barriers (e.g., moderately doped poly-Si), the low-frequency noise depends on the temperature. On the other hand, the noise signal in resistors with a lower potential barrier (e.g., heavily doped poly-Si) is characterized by rather weak temperature dependence. The experimentally observed behavior is in agreement with Eq. (2). It shows that the model of Luo is useful to predict the low-frequency noise in poly-Si and poly-$Si_{1-x}Ge_x$ resistors.

In conclusion, the noise properties of poly-$Si_{1-x}Ge_x$ are comparable with those of poly-Si at heavy boron doping levels. On the other hand, the noise in moderately doped resistors decreases with increasing Ge content. On the basis of their superior noise characteristics, poly-$Si_{1-x}Ge_x$ resistors are preferable to poly-Si resistors for analog circuit applications. For poly-$Si_{1-x}Ge_x$ with higher Ge content, the potential barrier of the grain boundary is lower than in poly-Si films, thereby reducing the noise from the grain boundary. Furthermore, we find that the noise in moderately doped resistors decreases with increasing temperature. These noise characteristics can be well predicted by using the carrier mobility fluctuation model.

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