Low-frequency noise analysis of Si/SiGe channel pMOSFETs

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Abstract

Low-frequency noise characteristics of 0.1 μm Si_{1-x}Ge_{x} channel pMOSFETs were studied by numerical simulations in the framework of the carrier number fluctuation model as well as the correlated fluctuation in the mobility model. Simulation results predict that Si_{1-x}Ge_{x} channel pMOSFETs could offer improved low-frequency noise performance as compared to the conventional bulk Si devices. This improvement in Si_{1-x}Ge_{x} channel pMOSFETs could be attributed to less effective oxide trap density for noise generation due to the increasing separation of quasi-Fermi level and valence band edge at Si–SiO₂ interface by Ge-induced band offset.

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1. Introduction

Recently, the rapid growth of the portable communication market requires the miniaturization of the whole system with as little power consumption as possible, leading to the trend of the integration of systems on a single chip. However, the competition between different device technologies to achieve integrated RF front-end transceivers on a single chip is not only based on single transistor performance, but is also related to other on-chip RF components and the future of VLSI manufacturability. Si/SiGe system has gained a lot of attention for RF/microwave telecommunication circuit application due to its enhanced carrier mobility and compatibility to the prevailing CMOS technology. It is reported that SiGe MOSFETs have enhanced carrier mobility, high-field drift velocity, and suppressed short channel effects [1], which are great benefits for high speed circuit applications. In addition to enhanced carrier transport properties and low power consumption, low-frequency noise performance is also very important in RF and microwave circuit applications because it is an important parameter for analogue applications, particularly for mixer and signal generation circuits where the low-frequency noise causes an unwanted phase modulation of the signal thus providing a limit on high speed communications. Therefore, the performance of low-frequency noise for SiGe MOSFETs is worthwhile to be investigated extensively.

Simulation of SiGe MOSFET noise can play an important role in realizing optimal CMOS RF circuit design by providing a priori noise performance metrics of devices and underlying technology issues. Flicker noise, the most dominant low-frequency (1/f) noise for MOSFETs, has been explained by two fluctuation theories: one is the number fluctuation based on the McWhorter’s charge trapping model [2] and another is the bulk mobility fluctuation based on Hooge’s hypothesis [3]. A unified model proposed by Hung et al. [4], which incorporates both the number fluctuation and the correlated surface mobility fluctuation mechanisms, can well explain the flicker noise in MOSFETs. Taking the high-field effects into account, the overall power spectral density of the normalized drain current noise \( S_{\text{ID}}/I_{\text{D}}^2 \) for short channel MOSFETs predicted by the unified noise model is [5]:

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\[ \frac{S_{ib}}{I_D} = \frac{\lambda k T}{2 W L^2} \int_0^L N_l(E_{ip}, y) \left\{ \frac{1}{N(y)} + \frac{\alpha(N) \mu(E)}{E} \right\}^2 \, dy \quad (1) \]

where \( \lambda \) is about 1 Å for carrier tunneling at the Si–SiO\(_2\) interface predicted by the WKB theory; \( k \), the Boltzman constant; \( T \), the temperature; \( W \), the channel width; \( L \), the channel length, and \( f \) the operating frequency. \( N \) is the number of carriers per unit area \((x, z\) plane) in the inverted channel, \( \mu \) the carrier mobility, and \( N_l \) the distribution of oxide trap concentration per unit volume in the oxide. Fluctuation in the occupancy of the oxide traps induces correlated fluctuations in the carrier number and surface mobility. The energy dependence of \( N_l \) enters into the expression for \( S_{ib} \) due to the variation of the quasi-Fermi level along the channel. The mobility scattering parameter, \( \alpha \), represents the influence of the oxide states on the carrier mobility. The input referred noise power \((S_{ib})\) could be obtained by dividing \( S_{ib} \) by the square of the transconductance \((g_m)\). In this work, we utilized this unified flicker noise model to study the low-frequency noise performance of 0.1 \( \mu \)m Si/SiGe pMOSFETs.

2. Device structure and simulation

Device structure studied in this work consists of a Si cap layer of 1 nm, a \( \text{Si}_{1-x}\text{Ge}_x \), \((0 \leq x \leq 0.5)\) channel of 5 nm, grown on n-type Si buffer. The gate oxide thickness is 30 Å and the gate electrode is made of p+-polysilicon (doping level of 1 \( \times \) 10\(^{20}\) cm\(^{-3}\)). A retrograde doping profile is used in the channel design with a low surface doping concentration of 10\(^{16}\) cm\(^{-3}\) in the cap/channel region and a high sub-surface doping in the ground plane \((10^{17}–10^{18}\) cm\(^{-3}\)). Representative S/D extensions (200 Å) and abrupt S/D junction (uniformly doped to 10\(^{20}\) cm\(^{-3}\)) with junction depth of 400 Å were included in this study.

A generic two-dimensional (2-D) device simulator, Medici [6], in which the Poisson’s equation and the current continuity equation are solved simultaneously, was used in order to model the electrical characteristics of \( \text{Si}_{1-x}\text{Ge}_x \) channel pMOSFETs with gate length of 0.1 \( \mu \)m. For heterostructures with abrupt interface changes in material properties and system variables such as potential or carrier concentrations, the thermal ionic-field emission and heterojunction tunneling models are self-consistently incorporated in the simulations. To account for the contribution of velocity overshoot effect in small geometry devices, the hydrodynamic model, which includes the effects of carrier heating by self-consistent solution of the drift–diffusion and energy balance equations, was used in the majority of calculations. A fully coupled solver was used to avoid numerical instabilities. The material properties of strained \( \text{Si}_{1-x}\text{Ge}_x \) including band gap, affinity, permittivity, carrier effective mass, effective density of states, and low-field hole mobility enhancement are appropriately accounted for [7–9]. The saturation velocity for holes in \( \text{Si}_{1-x}\text{Ge}_x \) is \( 1 \times 10^7 \) cm/s, which is taken the same as in Si. A Caughey–Thomas expression [9] for field-dependent mobility is used to account for the high-field effects on carrier mobility as shown in Eq. (2).

\[ \mu(E_y) = \frac{\mu_{eff}}{1 + \frac{\mu_{sat}}{v_{sat}}} \quad (2) \]

where \( \mu_{eff} \) is the low-field carrier mobility (which includes the effects of surface scattering and impurity scattering mechanisms), \( v_{sat} \) is the carrier saturation velocity, and \( E_y \) is the lateral \( E \) field along the channel.

The device electrical data, such as channel charge density \( N \), field-dependent mobility \( \mu \), and Fermi level along the channel, at a certain bias point were extracted by Medici simulation. These electrical data were then imported into Eq. (1) to evaluate the noise power spectral density. The physical parameter, oxide trap concentration \( N_t \), is empirically modeled [4] as a function of the position of quasi-Fermi level with respect to valence band edge \((E_{ip} – E_y)\). In this study, we assume the same oxide trap density distributions for Si and \( \text{Si}_{1-x}\text{Ge}_x \) pMOSFETs since they have the same Si/SiO\(_2\) interface. Realistically, the oxide trap density for SiGe MOSFETs is assumed one order higher than that for bulk Si MOS devices due to the necessity of low temperature gate oxide process for SiGe material system to prevent strain relaxation, which in turn will result in poor gate oxide integrity. The mobility scattering parameter, \( \alpha \), is a function of the local carrier density due to the screening effect and could be modeled by random telegraph signal data or by fitting to experimental data [10] \((\alpha = K_1 + K_2 \ln N\), where \( K_1 \) and \( K_2 \) are constants).

3. Results and discussion

The low-frequency noise characteristics of \( \text{Si}_{1-x}\text{Ge}_x \) pMOSFETs operated in linear and saturation regimes were simulated and compared to their counterpart Si bulk devices. To facilitate interpretation of the results, the spectra of the input-referred gate voltage noise \((S_{ib})\) and the normalized drain current noise level \((S_{ib}/I_D)\) were analyzed. Fig. 1 shows the low-frequency noise spectral \( S_{ib}/I_D^2 \) and \( S_{ib}/I_{sat} \) of \( \text{Si}_{1-x}\text{Ge}_x \) channel pMOSFETs as a function of gate overdrive simulated at \( f = 10 \) Hz and \( V_{th} = –0.05 \) V. It is clearly to see that the low-frequency noise spectral \( S_{ib}/I_D^2 \) and \( S_{ib}/I_{sat} \) of \( \text{Si}_{1-x}\text{Ge}_x \) pMOSFETs are significantly lower than the case of Si bulk devices over the entire range of gate overdrive and decrease with increasing Ge content in the \( \text{Si}_{1-x}\text{Ge}_x \) chan-
Based on the number fluctuation theory, one would intuitively expect a lower flicker noise for SiGe channel pMOSFETs because that holes confined within the SiGe channel due to the valence band offset are physically separated from the Si–oxide interface by a SiO cap layer, therefore, the random trapping and detrapping processes of channel charges in the oxide traps near the Si–SiO₂ interface are suppressed. Thus, the effective channel hole mobility increases due to higher intrinsic mobility in SiGe material and less surface roughness scattering. However, an examination of the flicker noise equation shows that this improvement in flicker noise is not simply due to the charge separation or mobility enhancement of the SiGe pMOSFETs. At very low drain voltages \( E_d \) is very small, the carrier density, Fermi level, and the oxide trap are assumed uniformly distributed along the channel and Eq. (1) becomes

\[
\frac{S_{D}}{I_{D}^2} = \frac{4kT}{e} \left( \frac{1}{N} + x(N)\mu_{\text{eff}} \right)^2
\]

Eq. (3) shows that the normalized drain current noise at low drain voltages is mainly affected by the channel charge density, carrier mobility, and oxide trap concentration. As the Ge concentration in Si₃₋ₓGeₓ channel increases from \( x = 0 \) to 0.5, the channel charge density slightly decreases while the carrier mobility is enhanced due to higher intrinsic mobility and hence, the sum of \( 1/N \) and \( x(N)\mu_{\text{eff}} \) increase accordingly as shown in Fig. 2. The tendency for increase of \( [1/N + x(N)\mu_{\text{eff}}] \) with increasing Ge concentration in Si₃₋ₓGeₓ channel could not well explain the lower flicker noises in SiGe pMOSFETs, which indicates that the improved flicker noise for Si₃₋ₓGeₓ channel pMOSFETs may come from the contribution of the oxide trap concentration \( N_t \) at the quasi-Fermi level.

It is known that oxide traps have energy levels distributed throughout the band gap with a U-shaped distribution across the band gap, that is, the trap density is relatively constant near the midgap, but it increases toward the band edges dramatically. Therefore, the absolute low-frequency noises spectral of Si₃₋ₓGeₓ channel pMOSFETs are expected to increase with gate bias since the oxide trap density increases abruptly as the hole quasi-Fermi level is brought closer to the valence band edge. For SiGe channel pMOSFETs, the separation of the hole quasi-Fermi level \( E_f \) at the Si cap surface is enhanced by the Ge-induced valence band offset. The higher Ge concentration in Si₃₋ₓGeₓ channel provides larger valence band offset between Si cap and Si₃₋ₓGeₓ channel, which results in higher valence band energy in Si₃₋ₓGeₓ quantum well and better hole confinement. The relative position of the hole quasi-Fermi level with respect to the valence band edge at the Si surface as a function of gate bias for various Ge content in Si₃₋ₓGeₓ channel is shown in Fig. 3. This Ge-induced valence band offset effectively pulls the hole quasi-Fermi level away from the valence band edge at the Si/SiO₂ interface and towards the midgap.
Fig. 3. Separation of the quasi-Fermi level of holes ($E_{fp}$) with respect to the valence band edge ($E_V$) at the surface as a function of gate voltage for Si$_{1-x}$Ge$_x$ MOSFETs.

region, hence reducing the oxide trap density effective for noise generation. This explains why the improved low-frequency drain current noise is enhanced with increasing Ge concentration in Si$_{1-x}$Ge$_x$ channel over the entire gate overdrive. As for the input referred voltage noise $S_{V_G}$, the improvement is further enhanced by the higher transconductance resulting from the higher intrinsic mobility in Si$_{1-x}$Ge$_x$ channels.

For MOSFET operating in the saturation region (under high drain bias condition), the field-dependence of the carrier mobility has to be taken into account and Eq. (1) becomes

$$\frac{S_P}{I_D} = \frac{jkT}{2f W L^2} \int_0^L \left\{ \frac{1}{N(y)} \pm \frac{z(N) \mu_{eff}}{1 + \left( \frac{z(N)}{N_{sat}} \right)^2} \right\}^2 dy$$  (4)

The simulated low-frequency noise spectral $S_P/I_D$ and $S_{V_G}$ for Si$_{1-x}$Ge$_x$ channel pMOSFETs at drain voltage of $-1.2$ V are shown in Fig. 4. Similarly, both of the $1/f$ noise spectral $S_{V_G}$ and $S_P$ decrease with increasing Ge content in the Si$_{1-x}$Ge$_x$ channel over the entire range of gate overdrive, which is in good agreement with the experimental data reported by Mathew et al. [11]. For 0.1 μm Si channel pMOSFETs, the noise $S_P$ for a drain voltage of $-1.2$ V (the saturation region) is smaller than for the $-0.05$ V drain voltage case (the linear region) by about 20–50% over a wide range of gate overdrive. This is because that the mobility-induced noise contribution is suppressed at high lateral fields present in short channel devices and the carrier number perturbation noise does not increase appreciably in the saturation region due to strong drain induced barrier lowering. For comparison, the low-frequency noise of long channel ($L_g = 1$ μm) MOSFETs operating in the saturation region has been found higher than the case in the linear region because the number noise increases due to a decrease in carrier density at the drain side of the device in the saturation region [5].

However, the tendency of noise reduction for Si$_{1-x}$Ge$_x$ MOSFETs at drain voltage of $-1.2$ V is suppressed with...
increasing Ge concentration as compared to the case at −0.05 V drain voltage (Fig. 5). This feature could be explained by the fact that carriers transporting through Si$_{1-x}$Ge$_x$ channels exhibit pronounced velocity overshoot phenomena due to higher intrinsic mobility and hence, the suppression of mobility-induced noise contribution at high lateral fields in short Si$_{1-x}$Ge$_x$ channel devices reduces with increasing Ge concentration. In addition, a strained Si$_{1-x}$Ge$_x$ p-channel with higher Ge concentration provides less gate-controlled depletion charges and lower electric field in the substrate due to better carrier confinement, which in turn cause higher potential barrier for holes flowing from source to drain [1]. Therefore, improved drain induced barrier lowering effect in Si$_{1-x}$Ge$_x$ channel will result in less carrier density at the drain side and hence, higher carrier number perturbation noise in the saturation region. This explains why the noise reduction of Si$_{1-x}$Ge$_x$ pMOSFETs operating in the saturation region is suppressed with increasing Ge contents as compared to the case in the linear region.

4. Conclusion

Using 2-D simulation, we have investigated the performance of low-frequency noise for 0.1 μm Si$_{1-x}$Ge$_x$ channel pMOSFETs based on a unified model which includes the oxide trap fluctuation theory and the correlated mobility fluctuation. The low-frequency noise improvement in Si$_{1-x}$Ge$_x$ pMOSFETs over Si bulk devices mainly comes from the separation of the hole quasi-Fermi level and the valence band edge at the surface is enhanced by the Ge-induced valence band offset and hence, the oxide trap density effective for noise generation decreases with increasing Ge concentration. This suggests that SiGe channel pMOSFETs have great advantages over Si bulk devices for RF/microwave circuit applications.

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References