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Electrical performance study of 25 nm Ω-FinFET under the influence of gamma radiation: A 3D simulation

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ABSTRACT

In this research paper, a 3D process simulation of 25 nm n-channel Ω-FinFET and the effect of Gamma radiation on device characteristics have been studied. Device simulations are carried out under the influence of Gamma radiation under varying does conditions from 100 Krad (SiO_2) to 10 Mrad (SiO_2). Effects of Gamma radiation on the threshold voltage, transfer characteristics, drive current, off-state leakage current and subthreshold characteristics have been studied. Extracted parameters for virgin and irradiated devices have been compared in order to understand the degradation in the electrical characteristics of the Ω-FinFET under study. Simulation results under the low drain and high drain bias has been reported and discussed. It is found that Ω-FinFET delivers better performance under irradiation as compared with conventional single gate MOS structures. Ω-FinFET is shown to be significantly tolerant to gamma radiation upto dose of 5 Mrad (SiO_2). In addition, the influence of quantum effects on this nanoscale device is investigated in detail. Sentaurus simulation results obtained has been compared with the reported experimental data.

1. Introduction

Understanding the effects of radiations on electronic devices is particularly important for space applications. The effects of radiation on single gate technologies have been widely studied. Due to scaling limit of classical CMOS structure, alternative devices are investigated. Multiple gate architectures are found to be the most promising solutions to overcome scaling limits [1]. In low dimensional FinFETs have emerged as one of the most promising candidates to replace current bulk CMOS technologies. However, these quasi-planar devices are inherently three-dimensional in nature. Therefore, to understand its electrical characteristics simulation should be carried in three dimensions.

Ω-FinFET was reported by Yang et al. [2,3]. It resembles to a large extent to Gate all around (GAA) FETs where Ω-shaped gate wraps most of the silicon finger. It produces enhanced control over channel and its manufacturing stages are same as bulk CMOS technologies. The cross-section of Ω-FinFET under study is shown in Fig. 1. Multiple gate devices are called Ω-FinFETs when the buried oxide is undercut.

Ω-FinFET tolerant upto 500 krad (SiO_2) to the total ionizing dose (TID) have been demonstrated [4] and comparative study of total ionizing dose effects in narrow and wide fin devices have been reported in [4]. Gate all around (GAA) structures are proved to be extremely insensitive to heavy ion irradiation and offers good resistance to gamma radiations [5,6]. The study presented in [7] illustrates the importance of taking into account quantum effects in the simulation of the device response when submitted to heavy ion Irradiation in GAA nanowire MOSFETs. The results presented by Castellani-Coulié et al. [8] was focused on heavy ion and it has been shown that bipolar amplification drastically increases when the OFF-state current increases and decreases when the film thickness is reduced. It has been shown that gate all around devices exhibit an excellent control of both impact ionization and bipolar amplification [8]. Experimental study by [9,10] reported that optimized narrow FinFET shows a drastically reduced influence to ionizing radiation. However, to the best of our knowledge, all the previous studies considered only classical approach. Quantum effects are investigated in ultrathin body and double gate devices to study single-event transient (SET) by [11]. In this paper we use 3D quantum mechanical numerical simulation for investigating electrical performance of Ω-FinFET.

The major issue elucidated in this paper is whether or not the high electrostatic control provided by the Ω shaped gate is good enough to prevent the electrical characteristics of scaled transistors from degradation induced by ionizing radiation. We show that the 3D carrier distribution is strongly affected by the quantum effects, which not only reduces the drain current but also modifies the recombination rate and the charge collection compared with the classical case.

In this paper, device and process flow for simulation of Ω-FinFET device is discussed in Section 2. The description of

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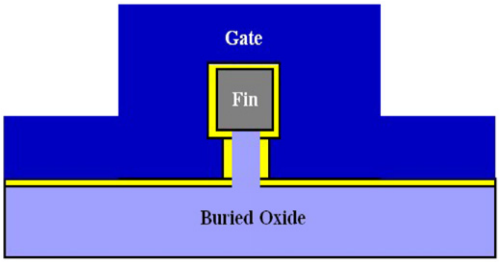

Fig. 1. Cross-section of Ω-FinFET.

radiation generation is given in Section 3. Effect of gamma radiation on mobility, transfer characteristics, threshold voltage, I_{ON}/I_{OFF} ratio and subthreshold characteristics has been described in Sections 3–8. Discussion on effects of trap charges is given in Section 9 and conclusions are drawn in Section 10.

2. Device and process description

The process flow reported by [2] is for 25 nm and by [3] for 35 nm is used here with slight differences in layer and mask thickness. The starting material is an SOI wafer with a top silicon layer thickness of 50 nm. The top silicon layer has initially a uniform substrate doping boron concentration of $5\times10^{18}\,\mathrm{cm}^{-3}$. Fin Mask is defined by sequence of processing steps that result in a 25 nm wide mask. Next step is to define the mask for the source/drain area for which the lift-off technique is used. By etching protective hard mask and silicon layer and then stripping intermediate nitride cuts out the dog bone shaped silicon patch, which will form the channel fin as well as the source and drain areas. To obtain an even better control of the gate over the channel, 7 nm of buried oxide is etched isotropically and, therefore, is slightly undercut. This makes room for the gate material to wrap around the channel fin. Stripping of hard mask and the rounding of the fin edges is done. After depositing 2 nm of gate oxide, the entire structure is filled with polysilicon. The gate mask is created then a mix of anisotropic (95%) and isotropic (5%) etching is applied, resulting is a gate length of 25 nm. An extension spacer is defined to prevent the penetration of the extension implants under the gate due to the inherent lateral straggle. The extension implantation with $2.5\times10^{13}\,\mathrm{cm}^{-3}$ dose and 7.5 KeV energy is performed. Thicker source and drain spacer is created. To ensure a relatively uniform doping in the source/drain area, phosphorus with $4\times10^{14}\,\mathrm{cm}^{-3}$ dose and 15 KeV energy is used. It penetrates deeper than arsenic and diffuses faster during activation/annealing. Subsequently rapid thermal anneal (RTA) for 1 s at 1025° K with a 3 s ramp up and a 2 s ramp down is done. Finally, the contact areas are etched free from the screening oxide and electrical contacts are defined for use in the device simulation. A schematic of the device architecture extracted is shown in Fig. 2.

After the process simulation, the transfer curves for a low drain bias ($V_{ds}=0.05$ V) and high drain bias ($V_{ds}=1.0$ V) are simulated and relevant electrical parameters, such as threshold voltages and drain current levels, were extracted. Radiation model, hydrodynamic model, bandgap narrowing Oldslotboom model, Philips unified mobility model, high field saturation models, compute the transverse electric field Lombardi model for computation of transverse electric field, Shockley–Read–Hall (SRH) generation recombination model and density gradient models for quantum effects are switched on in Synopsys Sentaurus [12–15]. Poisson, electron and hole continuity equations are solved in a self consistent manner using parallel iterative linear solver (ILS) available in device simulator for solving numerical simulations [12–15]. Simulations are also done for quantum and classical transport models under the conditions of irradiation and unirradiation. Various internal parameters are extracted through 3D simulations and the results are reported in the paper.

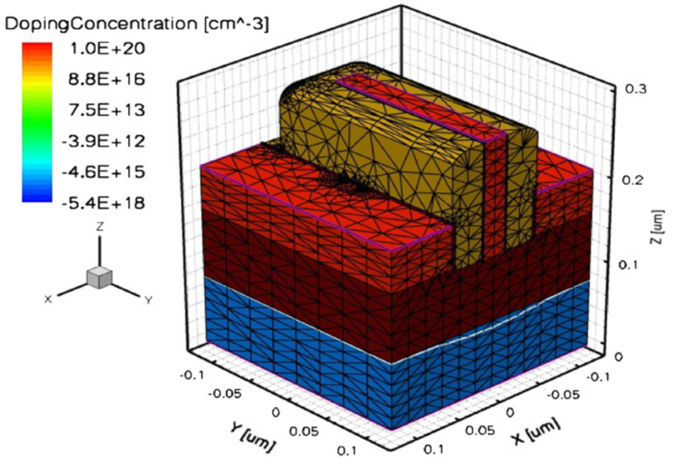

Fig. 2. 3D TCAD simulated structure of Ω-FinFET.

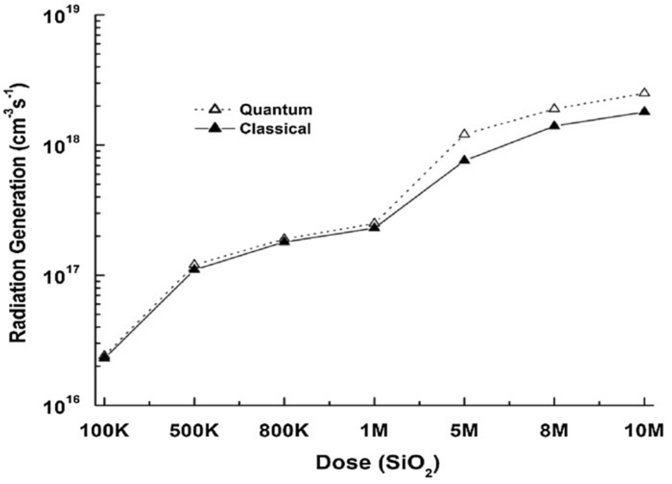

Fig. 3. Radiation generation against radiation dose.

3. Gamma radiation generation

Generation of electron hole pairs G_r, due to radiation is an electric field dependent process and is modeled [13] as

$$G_r = gD\left(\frac{E+E_0}{E+E_1}\right)^m \tag{1}$$

where D is the dose, g the generation rate of electron hole pairs and E_0, E_1 and m are constants. Dose (in rad) is changed over a time interval of 0.25 to 0.3 μs with a standard deviation of 0.05 μs of Gaussian rise and fall of the radiation exposure. Radiation generation rate due to varying dose of Gamma radiation is plotted in Fig. 3. The radiation generation rate in the channel fin increases with the dose of radiation. Generation rate at 100 Krad (SiO_2) dose under low drain bias for quantum transport is $2.04\times10^{16}\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ while for classic transport it is $2.3\times10^{16}\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$. However, generation rate at 10 Mrad (SiO_2) dose under low drain bias for quantum transport is $2.5\times10^{18}\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ and for classic transport it is $2.3\times10^{18}\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$. In the low injection regime, generated charges are not very high