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High Mobility Two-Dimensional Electron/Hole Gases on Relaxed GeSi Buffer Layers:Material Issues and Device Potentials

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A method for fabricating low threading dislocation density, thermally stable $Ge_x Si_{1-x}$ buffer layers on Si substrates with adjustable lattice constant (by changing x) is demonstrated. The key advancement is in the control of dislocation kinetics during lattice relaxation. Two-dimensional (2D) electron and hole gases with very high mobilities are fabricated on top of the $Ge_x Si_{1-x}$ buffer. Potential advantages and difficulties of using such 2D gases as the transport channels in FET's are discussed.

1. Introduction

A defect-free substrate with adjustable lattice constant will enable the realization of many electronic devices with long term reliability. If a buffer layer with the above characteristics can be integrated on Si substrates, the functionality of Si will be significantly expanded. We report our approach to this goal using relaxed GeSi buffers grown on Si substrates, together with selected applications using such structures.

2. Experiments

The basic structure consists a compositionally graded GeSi buffer layer grown on a Si (100) substrate, followed by a uniform GeSi layer to ensure total relaxation[1]. The typical rate of compositional grading is 10% Ge per mm for low threading dislocation densities (ρ_t). The structures were grown by MBE at high temperatures (900°C) and at a deposition rate of 3 Å/s.

The 2D gases are grown on top of the relaxed buffers. The active region of the 2D gases, however, is totally strained and grown at reduced temperatures (typically T<650°C). Si under tensile strain is used as the electron channel, and Ge under compressive strain is used as the hole channel. Fig.1 shows a 2D electron gas structure[2].

Electron beam induced current (EBIC) is used as the primary technique in counting ρ_t's[3]. TEM is used as a supplemental technique to examine the dislocation morphology mainly in cross-section. Temperature dependent sheet charge density and mobility are measured using Van der Pauw geometry.

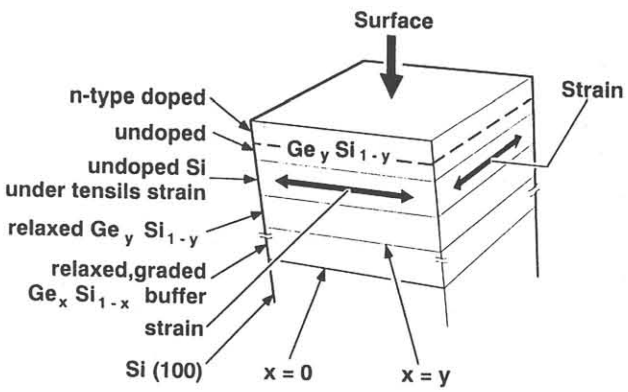

Figure 1. Schematic drawing of the layer structure of the two-dimensional electron gas.

3. Results and Discussion

Fig.2 shows the cross-sectional TEM of a typical structure with graded GeSi buffer with the final composition being 30% Ge. One can see that the structure has very high density of misfit dislocation density but low ρ_t. The typical value of ρ_t for this kind of structures is $10^6 cm^{-2}$ as measured by EBIC. We found that the wet chemical defect etch as commonly used for Si can not be used to determine ρ_t in these structures, presumably because the strain field from the underlying misfit dislocation networks in the relaxed buffers interfere strongly with the strain field of the threading ends which makes it very difficult to delineate the threading ends by etching. Orders of magnitude errors can easily result using the conventional defect etching.

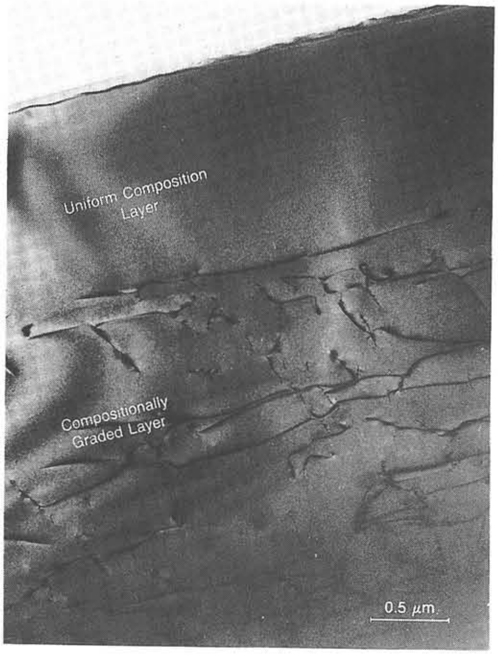

Figure 2. Cross-sectional transmission electron micrograph of a compositionally graded GeSi structure with a final composition of 30% Ge and a 1 μm thick uniform $Ge_{0.3}Si_{0.7}$ cap layer.

The reduction in ρ_t's comes from the suppressed dislocation nucleation and the increased dislocation propagation as the result of the compositional grading. Scribe and anneal experiments showed that the dislocation interaction is reduced in a graded structure which effectively enhances the dislocation propagation.

The temperature dependent sheet charge densities and mobilities (μ's) for the 2D electron and hole gases are shown in fig.3 and fig.4, respectively. The best 4.2 K μ's we have measured are 180,000 cm^2/V-s for electrons and 55,000 cm^2/V-s for holes. The strain in the channels altered the energy band structures significantly. In the case of 2D electron gas, the in-plane tensile strain lowered the energy of the two equal potential ellipsoids (with their long axis perpendicular to the 2D plane) relative to the other four of the Si conduction band. The in-plane effective mass (m_{eff}) of the 2D electron gas is consequently reduced to $0.2m_0$, the transverse m_{eff} of an individual ellipsoid. The mechanism is more complicated in the 2D hole gas case. The interaction of the in-plane compressive strain with the three bands of the Ge valence band resulted in a hole density dependent m_{eff}, i.e. the valence band is highly nonparabolic. This behavior has been eluded by theory[4]. The lowest 2D hole m_{eff} we measured is $0.04\pm0.01m_0$ at a 2D hole density of 4.2×10^{11} cm^{-2}, which is lighter than even the electron effective mass of GaAs ($0.067m_0$).

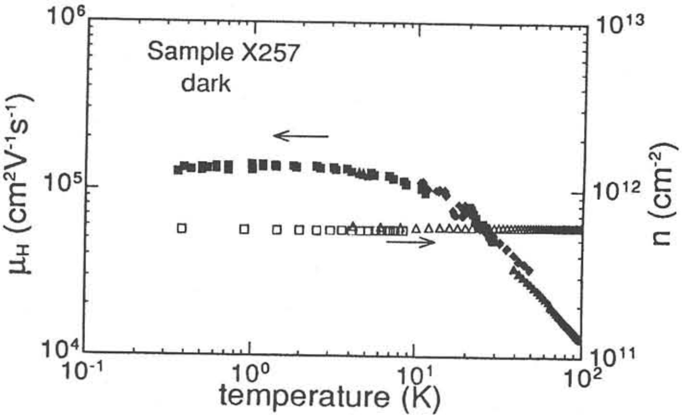

Figure 3. Measured electron mobility and sheet density versus temperature for one of the two-dimensional electron gas structure which has a 4.2 K mobility of ≈156,000 cm^2/V-s.

Room temperature mobilities of both the 2D electron and hole gases are significantly higher than their bulk counterparts. This is because the μ's at room temperature are limited by acoustic phonon scattering, and are thus inversely proportional to the m_{eff}'s. The lighter m_{eff}'s result in higher μ. Room temperature μ of similar 2D electron gases has been reported to be as high as 2800 cm^2/V-s[5]. The presence of parallel channels and the contact leakage prevent us from obtaining accurate measurements of room temperature m's for the 2D hole gases. We expect it to be higher than the electron mobility in bulk GaAs based on the m_{eff} comparison.

4. Field Effect Transistor (FET) Application Potential

Depends on the FET channel length regime, a higher mobility could translate into improved transconductance (g_m) for a given gate length. Such improvement has been demonstrated[6][7]. The potential for the commercialization of GeSi based FET integrated circuits (IC), however, hinges on the processing compatibility with the existing Si CMOS technology. On that front, the requirement for lower thermal budget is the main issue that one has to deal with. In addition, the gate oxide growth and the method for isolation also appear to be tough challenges. As a result, several critical processing steps, such as the poly-gate doping, the quality of gate oxide, and the self-aligned gate definition will have to be brought under control before the GeSi based FET can be used for IC applications.

5. Summary

The use of compositionally graded buffer layers offers a promising approach for fabricating low defect buffer layers on Si substrates with adjustable lattice constants. High mobility 2D electron and hole gases have been fabricated on top of such buffer layers of GeSi. The room temperature

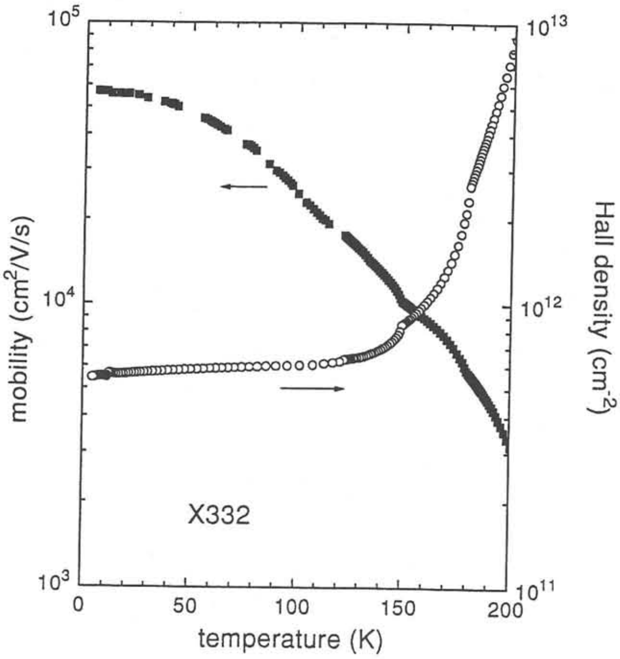

Figure 4. Measured hole mobility and sheet density versus temperature of one of the two-dimensional hole gas samples which has a 4.2 K mobility of ≈ 55,000 cm^2/V-s.

mobilities of the 2D gases are significantly improved from the 3D values, which opens up the possibility of using these 2D gases for high performance FETs.

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