Experimental Study of Defect Behaviors in Germanium

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BY

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主論文要旨

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主論文題目：

Experimental Study of Defect Behaviors in Germanium
（ゲルマニウム中の欠陥挙動に関する実験的研究）

（内容の要旨）

半導体集積回路の性能は，シリコン(Si) MOSFET (metal-oxide-semiconductor field-effect-transistor)の微細化により向上されてきた．しかし，MOSFETのゲート長が 100 nm 以下に到達するとデバイス特性のばらつきの増大やリーク電流増大などの様々な問題が顕著化し，微細化のみに頼るデバイスの性能向上は物理的限界に近づいている．そこで，キャリア移動度がSiの３倍以上と高く，既存のSi集積回路との融合も容易な半導体ゲルマニウム(Ge)が，新しいMOSFETのチャネル材料として注目を集めている．本研究では，現在のSi MOSFET集積回路の特性を上回るGe MOSFET集積回路の実現に向けて，Ge MOSFETの作製過程の理解の基盤を成すGe点欠陥およびGe表面の挙動解明を目的とした実験に取り組んだ．

第一章では背景を述べ，第二章では，ソース・ドレイン領域形成のための砒素(As)不純物イオン注入の母体Geへの影響を定量化する．固体ソース分子線エピタキシーを用いて安定同位体 ^{70}Geと天然同位体組成を有するGeを原子層単位で交互に積層した同位体超格子を作製し，その表面からAsをイオン注入した．注入されたAsイオンと衝突した母体Ge原子は移動し，その結果，Ge超格子の周期性が乱れて一部は非晶質化した．この母体Ge原子の深さ方向の平均移動距離を，二次イオン質量分析(SIMS)による^{74}Geの深さ方向濃度分布の測定から決定した．さらに，試料断面の透過型電子顕微鏡観測により非晶質化した領域を特定することから，Ge原子が 0.75 nm 以上動いた場合に非晶質化が誘発されることを明らかにした．この臨界値 0.75 nm は，注入ドーズ量に依存しない普遍性を有することも分かった．第三章では，二軸性圧縮歪を有するGe中において，Ge自己拡散係数が上昇することを示す．Ge同位体超格子を緩和 Si$_{0.2}$Ge$_{0.8}$ 層で挟み込むことにより，二軸性圧縮歪を有するGe同位体超格子を作製した．この試料を，様々な温度と時間で熱処理することにより，圧縮歪Ge中のGe原子を自己拡散させた．拡散後の ^{74}Geの深さ方向濃度分布をSIMSにより観測することから，圧縮歪Ge中の自己拡散係数を決定した．二軸性圧縮歪によりGe自己拡散は増速され，その増速度は，自己拡散を担う空孔欠陥周囲の局所体積変化を考慮した理論的モデルと定量的に一致することを示した．第四章では，Geナノワイヤからの近赤外フォトルミネッセンス(PL)特性を示し，ナノ構造で顕在化する電子構造に対する表面の影響を議論する．化学気相蒸着を用いてSi基板上に直径 40 nm のGeナノワイヤを垂直方向に成長し，Geナノワイヤからの近赤外波長領域のPLを初めて観測することに成功した．近赤外PL波長の試料温度・レーザー強度依存性を調べることから，その発光が直接再接合に起因することを明らかにした．また，Geと自然酸化膜界面の準位を介した非発光再結合の寿命を見積もることから，それらの準位によるキャリアの捕獲が間接再結合による発光を抑制したという仮説を導く．第五章では本研究のまとめを述べる．

SUMMARY OF Ph.D. DISSERTATION

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Title

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Abstract

Improvements of semiconductor integrated circuit (IC) performance have been driven mainly by miniaturization of silicon (Si) MOSFET (metal-oxide- semiconductor field-effect-transistor). However, with the gate length reaching 100 nm and below, various issues such as the increase of the leakage current, characteristic variability among many transistors, and emergence of quantum effect start to limit the advancement. Therefore, industry is seeking for reliable methods to improve the IC device performance that can be adopted in parallel to the conventional scaling approach. A partial substitution of widely used Si with germanium (Ge) is one of them because of its intrinsic electron and hole carrier mobilities that are higher by more than a factor of three compared to those of Si. Realization of Ge MOSFET whose characteristic is comparable or even higher than state-of-the-art Si CMOS, however, requires enormous efforts covering the full range between basic research and production. The present thesis focuses on understanding of defect and surface properties that will be of importance to future designing of Ge MOSFET devices and fabrication processes.

After introduction of the background in Chapter 1, Chapter 2 discusses the experimental observation of host-Ge displacements as a result of arsenic (As) impurity ion-implantations. Ge isotope superlattices (SLs) composed of alternating layers of stable isotope ^{70}Ge and naturally available Ge were grown by solid-source molecular beam epitaxy followed by As ion-implantation from the surface. Ge atoms were displaced by the collisions with implanted As ions leading to smearing of the periodicity of the Ge isotope SLs and turning heavily displaced region into the amorphous state. The average distance of the Ge displacements as a function of depth was determined from the depth profiles of ^{74}Ge measured by secondary ion mass spectroscopy (SIMS) for each sample implanted with different condition. Cross-sectional transmission electron microscopy was employed in parallel to identify the amorphous regions to reveal that amorphization occured when the Ge displacements exceeded 0.75 nm. This critical value, 0.75 nm, was found to be independent of implantation doses. Chapter 3 presents an experimental investigation to probe Ge self-diffusivities in biaxially-compressed Ge layers. Growth of a compressively strained Ge (s-Ge) isotope SL was conducted by sandwiching a Ge isotope SL by relaxed $Si_{0.2}Ge_{0.8}$ layers. Diffusion annealing with various temperatures and durations induces Ge self-diffusion within the strained SLs without releasing the strain. The self-diffusivities in compressively s-Ge were determined from the SIMS depth profiles of ^{74}Ge in the SLs. The self-diffusion was enhanced by the compressive biaxial strain with the degree of the enhancement being consistent quantitatively with a theory that considered local volume changes of Ge lattices around vacancies which were responsible for the diffusion. Chapter 4 presents near-infrared (NIR) photoluminescence (PL) studies of Ge nanowires (NWs) to probe the effect of the surfaces (Ge/native oxide interfaces) on the electronic properties of Ge nanostructures. Ge NWs with a 40 nm diameter were synthesized on a Si substrate by chemical vapor deposition. The dependence of the observed PL peak position on temperatures and excitation laser powers confirmed that we observed a PL peak originating from direct-band-gap recombination in the Ge NWs for the first time. While this observation confirmed the high quality of the present Ge NWs, the diameter 40 nm was still too large to turn the Ge into direct-gap semiconductors. A simple analysis is presented to show that the absence of indirect-band-gap PL from the Ge NWs is most likely due to the fact that the non-radiative recombination rate at the Ge/native oxide interfaces is much faster than recombination via indirect band gap. Chapter 5 presents over all summary and conclusions of this study.