Continuum Modeling of Indium to Predict SSR Profiles

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Abstract

Indium (In) diffusion and dose-loss in silicon is modeled in a continuum simulator. The model includes the large segregation of In to End of Range (EOR) defects, and the dissolution of these defects resulting in dose-loss of In at the surface. The models developed are successfully applied to predict state of the art (90 nm) transistor performance.

1 Introduction

Aggressively scaled CMOS devices require a super-steep retrograde (SSR) channel profile for good control of short channel characteristics. nMOS devices typically use boron as a halo dopant; however boron exhibits transient enhanced diffusion (TED) and results in non-abrupt halo dopant profiles. Indium, on the other hand preferentially segregates into the oxide resulting in a natural retrograde profile at the oxide/silicon interface (example Fig. 1). As-implanted In also has less straggle due to its larger atomic mass resulting in more abrupt profiles. Indium is thus aptly suited for use as a halo dopant for achieving a SSR profile. The use of In is however complicated by the excessive dose-loss during annealing. The inability to achieve high In active concentrations (illustrated in Fig. 2) adds a new dimension of complexity to device design with In halo. For example, additional boron maybe required to achieve the target off-current. Hence, a good understanding of In dose-loss is needed to better understand the trade-offs associated with co-doping of boron and In. In this work, we develop process models based on an understanding of In TED and dose-loss. These models are used in a TCAD environment to explore and optimize 90nm nMOS transistor performance with In SSR.

2 Diffusion of Indium in Silicon

Indium is primarily an interstitial diffuser despite its large atomic radius [1]. Consequently In exhibits Transient Enhanced Diffusion (TED) similar to boron [2]. Low temperature experiments are a useful means to probe TED effects. Annealing at lower temperatures result in anomalous In redistribution (example see Fig. 3). After a low temperature anneal, the location of the peak is displaced while the tail undergoes no diffusion. During a typical high temperature activation process significant dose of In is lost from silicon. It is necessary to understand both these temperature regimes to comprehend In diffusion in silicon.

Low temperature diffusion: Amorphizing In doses were implanted and regrown at temperatures that result in solid phase epitaxy (SPE). Fig. 3 shows the SIMS results after a 585°C/45min anneal. 90% of the implanted dose is within the silicon after the anneal. This suggests minimal dose-loss associated with the regrowth of the amorphous layer. Fig. 3 also shows simulations from a Monte Carlo implant (TRIM) with the net interstitial profile. The $2^{\rm nd}$ In peak corresponds to the location of the amorphous/crystalline (*a/c*) interface. This suggests In is decorating the EOR defects. Infact, Noda $et\ al.$ correlated the peak In redistribution to EOR loop evolution [4]. They developed a model for In profile evolution arising from decoration of EOR loops. However, the thermal budget of our experiment is too small to allow loop evolution. To understand this process better, we look at the evolution of small interstitial clusters. A multi-cluster model for interstitial defects (I_n and $\{311\}$'s) is used for this simulation [5]. The model is well calibrated to data on interstitial super-saturation [6]. Fig. 4 shows the time evolution of the average size (n) of the interstial clusters (total concentration in interstitial clusters/total number of interstitial type defects). The majority of excess interstitials are present as small clusters ($n < 15$) during the anneal. This suggests In agglomeration with small interstitial clusters. Further, as shown in Fig. 5 In segregation to the EOR region can be suppressed by the presence of substitutional carbon, a known interstitial getter. Hence, a model based on decoration of In to interstitial clusters is added. A buried amorphous layer (200–400Å) is used for the simulations. Fig. 6 shows a good match to the In redistribution at such low temperatures. The presence of $\mathrm{In}-\mathrm{I}_n$ clusters reduces the tail motion, whereas the peak of the implant in the regrown region is mobile.

High temperature diffusion: Indium diffusion at high temperatures is dominated by dose-loss. Almost 50% of the as-implanted dose is lost to the oxide during the anneal (Fig. 2). The interstitial rich In clusters dissolve during the high temperature anneals. The excess interstitials from the dissolving I_n clusters result in TED of In. The released In from the dissolving clusters are also swept towards the surface accelerated by the interstitial flux to the surface. This results in dose-loss of In. Fig. 7 shows calibration to dose-loss data after a $1050^\circ\mathrm{C}$ spike anneal. Increasing the In dose results in increased formation of In interstitial clusters. A large dose of In is thus lost during their dissolution.

Application of Process Model The calibrated models are incorporated into a process/device simulator for evaluating the impact of a SSR profile on a nMOS device. Our simulations, (corroborated with data) of nMOS devices at various gate lengths predict a better $\mathrm{V_T}$ rolloff for the In halo (Fig. 8). The SSR halo produced by In improves immunity to short channel effects.

3 Conclusions

Channel profile engineering with In is challenging, despite the inherent advantages of indium to produce a SSR channel. A model based on agglomeration of indium to EOR interstitial defects predicts the anomalous low temperature redistribution of indium. Dose-loss of indium is modeled by the dissolution of these defects at higher temperatures. Models calibrated to dose-loss data predict improved $\mathrm{V_T}$ rolloff with indium halo.

References

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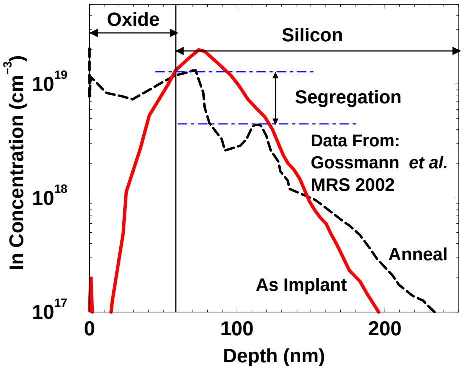

Fig. 1: Figure illustrating segregation of indium into oxide from silicon resulting in an retrograde profile.

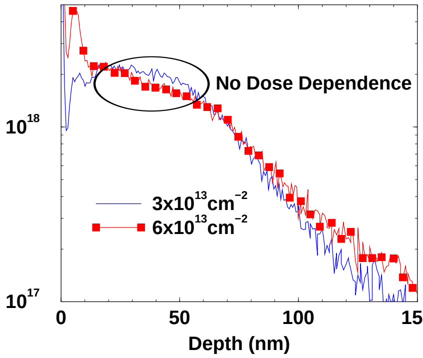

Fig. 2: Data illustrating the dose dependence of annealed In profiles. Almost 50% of the implanted dose is lost during annealing. A 2x increase in indium implant dose results in negligible increase in peak concentration.

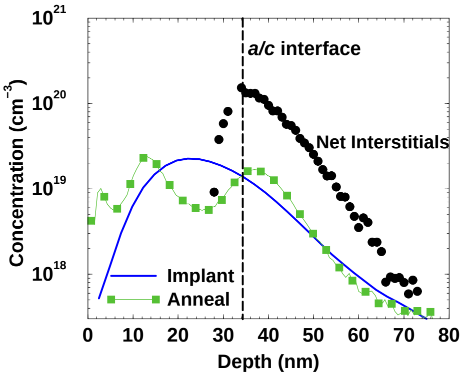

Fig. 3: A low temperature anneal shows anomalous redistribution of indium after a 585°C anneal. The peak of the indium is highly mobile compared to the implant tail. The redistributed indium profile overlaps the as-implanted interstitial rich region (from TRIM) indicating a In/I interaction.

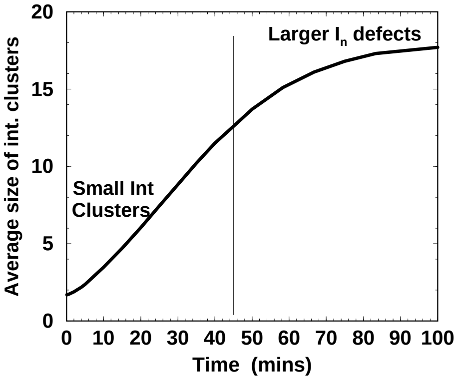

Fig. 4: Simulations showing average size of interstitial clusters during the low temperature 585°C anneal. Due to the slow kinetics, most of the interstitials are present as small clusters. This suggests indium agglomerates with small interstitial clusters prior to the formation of larger {311} defects or loops.

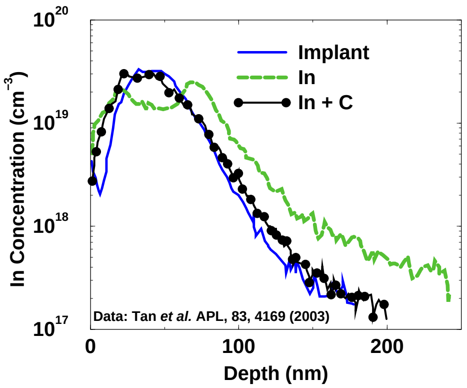

Fig. 5: Impact of substitutional carbon (a known interstitial getter) on In diffusion. The supression of EOR interstitial defects reduces the formation of indium/interstitial defects. Hence no anomalous behavior is observed.

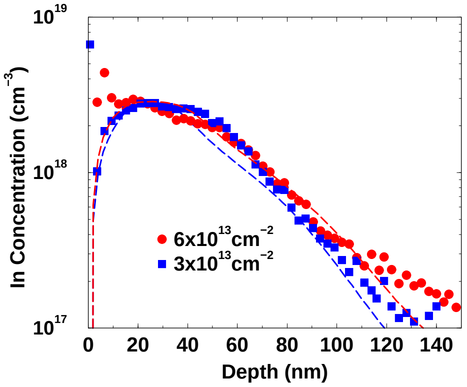

Fig. 7: Comparison of simulations to indium profiles in silicon after a 1050°C anneal. The dissolution of the EOR defects during annealing results in TED and dose-loss.

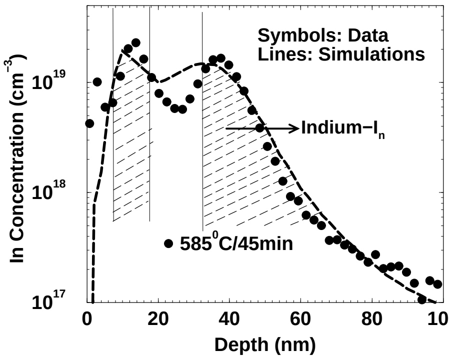

Fig. 6: A model based on In-I_n clusters captures the low temperature diffusion well. The peak of the indium in the amorphized region is highly mobile and is pulled into the interstitial rich layer, arising from trapping of indium by the I_n clusters.

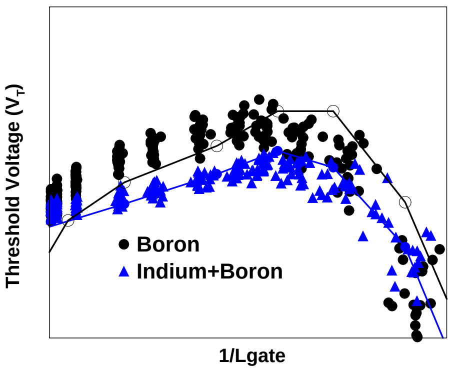

Fig. 8: Application of model to device simulation shows the formation of an SSR channel profile with In. Electrical data supports the simulations.