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Chemical Mechanical Polishing of Epitaxial Germanium on SiO$_2$-patterned Si(001) Substrates

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Aspect Ratio Trapping is a promising technique for heterointegration of Ge onto Si substrates. By growing Ge in patterned SiO$_2$ trenches, lattice-mismatch dislocations arising from the epitaxial interface can be effectively trapped. However, planarization of these samples is required to enable device fabrication. This paper describes the development and optimization of a chemical mechanical polishing process for these structures. Polishing using diluted Nalco 2360 slurry was investigated, with the addition of NaOCl, NH$_4$OH, or H$_2$O$_2$, for Ge removal rate increase. A slurry mix consisting of Nalco 2360, H$_2$O$_2$, and DI water was shown to have low dishing and low surface metals contamination, and planarized the Ge Aspect Ratio Trapping samples very effectively.

Introduction

Ge or III-Vs integrated on Si substrates are a promising path to high performance complementary metal-oxide-semiconductor (CMOS) field-effect transistors (FET) due to their high carrier mobility. Aspect Ratio Trapping (ART) has been demonstrated as a compelling, CMOS-compatible heterointegration solution (1-3). In this method, lattice-mismatch dislocations arising from selective Ge growth on a Si substrate are trapped between vertical oxide sidewalls, allowing growth of high-quality epitaxial Ge above the defect-trapping region, as shown in Figure 1a. The heterointegration of Ge and III-V materials with silicon is expected to be useful for a wide variety of applications, including non-Si channel MOSFETs, as depicted in Figure 1b. The subject of this paper is the planarization of Ge grown in oxide trenches on a Si substrate, to make these regions suitable for subsequent device fabrication.

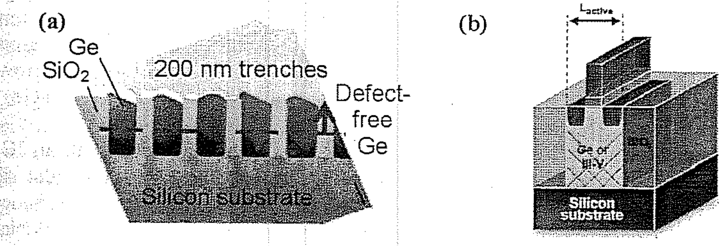

Figure 1. (a) Cross-sectional TEM image of defect trapping in 200nm trenches of Ge ART structure. Ge region above the dashed line is defect-free. (b) Schematic of proposed device structure, showing trapped defects.

Background

Chemical mechanical polishing (CMP) of Ge in the past has been primarily limited to blanket Ge or Ge-on-insulator (GeOI) films (4,5). However, very little information about the actual Ge CMP process has been published. In a study of blanket Ge CMP, for the purpose of eliminating long-range crosshatch roughness in Ge grown via a SiGe graded buffer on silicon (6), a standard oxide CMP slurry (KOH and colloidal silica) was found to have a low removal rate on pure Ge. Preferential etching of the Ge led to pitting without eliminating the crosshatch roughness. Ultimately, polishing an oxide layer deposited on the Ge was developed as an alternative approach (6). Other researchers have investigated cleaning of Ge blanket layers following CMP, but do not describe in detail their CMP process (7).

Some useful Ge CMP process information has come out of work on micro-electro-mechanical systems (MEMS), with one group describing the planarization of a composite Ge-Si structure consisting of a sacrificial layer of Ge in patterned Si (8). The removal rate and sample topography were evaluated for several slurry abrasives and chemistries. Low solids concentration of 300nm alumina in a 1-5% NH_4OH-based solution planarized an original step height of 2μm to below 100nm (9), a CMP application significantly different from this work.

In this paper, we describe the development of a CMP process for planarizing the Ge-SiO_2 composite structure produced by Ge growth in SiO_2 trenches on a Si wafer. To be suitable for subsequent device fabrication, the wafers were required to have minimal dishing of the Ge regions and low levels of metallic contamination. A conventional silica slurry was used for this work, with added NaOCl, NH_4OH, or H_2O_2 to attempt to increase the Ge removal rate. Each slurry mixture was tested to determine the polish selectivity of Ge versus SiO_2, as well as dishing, overpolish, and surface metals levels. Optimization of the process followed, to find the most favorable slurry composition, and to establish a post-CMP clean. Finally, the CMP of 'coalesced' versus 'uncoalesced' Ge ART samples was evaluated to determine the best approach.

Experimental

Epitaxial Ge was selectively grown in patterned trenches on Si wafers of 200mm diameter (1). The patterned wafers consisted of trenches etched into thermally-grown 500nm-thick SiO_2. These trenches varied in width (between 200 nm and 450 nm), as well as spacing between adjacent trenches. Most of the samples for CMP were grown to coalescence, 400nm-1000nm above the oxide trenches. Epitaxial Ge was also grown on bare Si wafers, and these wafers were used to measure the polish rate on blanket Ge.

CMP was performed on either a Strasbaugh 6EC or an IPEC 472 with an IC1000 stacked pad and variable concentrations of Nalco 2360 slurry (70nm colloidal silica). Either NaOCl, NH_4OH, or H_2O_2 solution was added to the diluted slurry to enhance the Ge removal rate. (Reagent concentrations of those additive solutions were 6% NaOCl, 30% NH_4OH, or 30% H_2O_2.) Each slurry mix consisted of part Nalco 2360, part chemical additive, and the remainder DI water, adding up to 100% of the slurry mix. Concentration percentages listed beyond this point refer to the fraction of Nalco 2360, NaOCl solution, NH_4OH solution, H_2O_2 solution, or DI water in the slurry mix. The range of additive fraction in the slurry mix was 0-2.4% of NaOCl, 0-100% NH_4OH, or 0-10% H_2O_2. The CMP process consisted of 10 seconds of ramp-up, a polish step, and 25 seconds of ramp-down and rinse steps. Polish time was varied. The down-force was 3 PSI, and the slurry feed rate was 150mL/min during the polishing step, with in-situ diamond pad conditioning. A Verteq Goldfinger megasonic post-CMP clean using only DI water was used for most Ge and Ge ART samples. A diluted SC-1 solution was used in the megasonic clean for all wafers with an oxide film.

Evaluation of the material removal rate (RR) was based on CMP of blanket oxide and Ge films on Si. Pre-CMP and post-CMP film thicknesses were measured by interferometry (Filmetrics) or ellipsometry (Sopra GE-S5). Endpointing of the patterned ART samples was achieved initially by visual and optical microscope inspection, and later by calibrating CMP process time with cross-sectional scanning electron microscope (SEM) analysis. The patterned ART samples were cleaved to measure film thicknesses in an Amray 3300FE or Zeiss Supra 40 field-emission SEM. Transmission electron microscopy (TEM) samples, prepared by mechanical polishing and Ar ion milling, were observed in a JEOL JEM 2100 TEM. VPD-ICP-MS was used to measure the level of metallic contamination on the surface of bare silicon or blanket oxide wafers after CMP.

Slurry Investigation

Slurry mixtures of diluted Nalco 2360 alone and combined with either NaOCl, NH_4OH, or H_2O_2 were tested for their suitability for CMP of Ge. The primary factors tested were selectivity, removal rate, and post-CMP surface metallic contamination levels. The target Ge:SiO_2 polishing rate ratio (selectivity) was about 5:1. Excessive dishing of the Ge film was anticipated if the selectivity was greater than about 5:1, while overpolish of the Ge and SiO_2 was anticipated if selectivity was less than about 5:1. Results for each slurry mixture are described first; followed by selectivity and metals data.

Diluted Nalco 2360

Wafers were polished with Nalco 2360 slurry, diluted with de-ionized (DI) water. The CMP removal rates were determined for slurry mixtures with concentrations of Nalco 2360 varying from 4.5% to 100%. Results for oxide RR for all slurry mixes attempted (including those with additives) and selected Ge RR data (at 100% and 0% Nalco 2360) are shown in Figure 2. The Ge RR is not significantly affected by the Nalco 2360 concentration, but the oxide RR is directly related to the amount of Nalco 2360 in the slurry mix.

Oxide Removal Rate (All Slurry Mixes) As demonstrated in Figure 2, Nalco 2360 concentration is the major factor controlling the oxide RR. While the additives appear to have some effect on the oxide RR, the removal rate of a slurry mix with additives appears to follow the same general trend as one without additives, for the concentrations tested. Using diluted slurry alone, the preferred selectivity (Ge faster than SiO_2) was not achievable for any concentrations because of a significant equipment vibration.

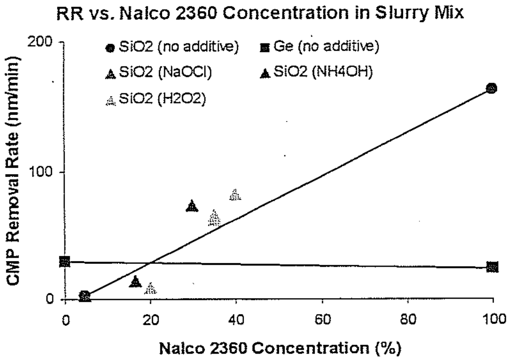

Figure 2. SiO_2 removal rates as a function of slurry concentration and for various chemical additive conditions. Ge polished using no additives is included for comparison.

Vibration Abatement The Nalco 2360 slurry was originally recommended as a possible slurry which would be selective in polishing Ge rather than SiO_2. An unexpected result of this selection was significant CMP tool vibration when polishing oxide wafers (and nearly-cleared Ge ART wafers) with slurry mixes containing low concentrations of Nalco 2360 in DI water. Vibrations were not observed during testing with NaOCl, but significant vibrations were observed using NH_4OH and H_2O_2 additives. These vibrations are believed to be caused by high levels of friction between the wafer and the pad for some slurry mixtures. They were evident only when polishing oxide, and not when polishing Ge films.

NaOCl acts as an additional lubricant at the wafer-pad interface, while the NH_4OH and H_2O_2 do not (10). Whereas ~4.5% Nalco 2360 in the slurry mix polished oxide without vibrations when NaOCl was used, minimum Nalco 2360 concentrations of 30-35% were necessary to eliminate vibrations using NH_4OH and H_2O_2 additives. The additional spherical colloidal silica particles in the slurry mix appear to moderate the friction at the oxide-pad interface. The vibrations prevented testing the SiO_2 polish rate for low Nalco 2360 concentrations in slurry mixes containing NH_4OH, H_2O_2, or no additive.

Diluted Nalco 2360 with NaOCl added

The incorporation of up to 2.4% NaOCl in the diluted Nalco 2360 slurry mix increases the Ge RR, as shown in Figure 3. The NaOCl-additive experiments were run at ~4.5% Nalco 2360; the tool vibration was not observed while using NaOCl in the slurry mix. Cross-sectional SEM results in Figure 4 clearly illustrate the significant dishing at 1.4% NaOCl. While overpolish is evident as well, the level of dishing on this sample is unacceptably high. It may be possible to reduce the amount of dishing by reducing the concentration of NaOCl and adjusting the polish time.

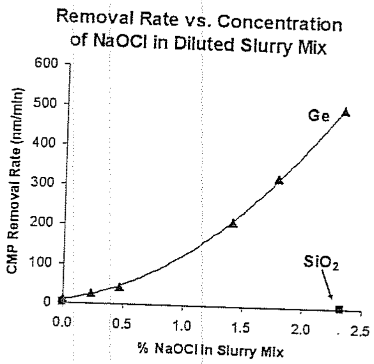

Figure 3. Ge and SiO_2 removal rates determined for slurry mixes containing NaOCl additive at low Nalco 2360 concentrations.

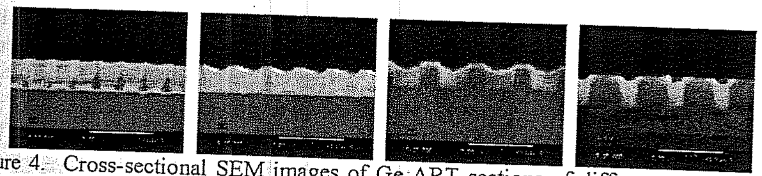

Figure 4. Cross-sectional SEM images of Ge ART sections of different trench widths polished with 1.4% NaOCl and 4.7% Nalco 2360 in the slurry mix.

Diluted Nalco 2360 with NH_4OH added

Adding NH_4OH to the diluted Nalco 2360 slurry did not enhance the Ge RR significantly. Neither NH_4OH concentrations below 10% with diluted slurry nor 100% NH_4OH alone appreciably affected the RR, shown in Figure 5. With oxide removal rates at a minimum of 70 nm/min to avoid vibration, the preferred selectivity (Ge faster than SiO_2) was not achievable for any concentrations.

One Ge ART sample was polished despite vibrations at 2.8% NH_4OH and 4.6% Nalco 2360, where the Ge RR was expected to be higher than the oxide RR (oxide RR could not be measured at this low slurry concentration because of vibration). Cross-sectional SEM images of this sample are shown in Figure 6. This sample is endpointed perfectly for the patterns in the left-most and right-most images. Dishing is slightly less significant for this sample compared to the NaOCl sample, but polishing could not regularly occur using this slurry mix because of the vibration.

Diluted Nalco 2360 with H_2O_2 added

A slurry mix with low concentrations of H_2O_2 (>0.05%) polishes Ge selectively to SiO_2 (Figure 7), even with 35% Nalco 2360 to avoid vibration. A sample polished with 0.16% H_2O_2 is shown in Figure 8. Observed dishing amounts are acceptable in these pattern areas, and overpolish can be controlled by endpointing to a specific pattern of interest.

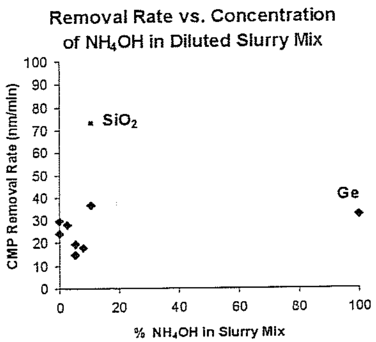

Figure 5. Ge removal rates determined for slurry mixes containing NH_4OH additive. Minimum oxide polish rate indicated.

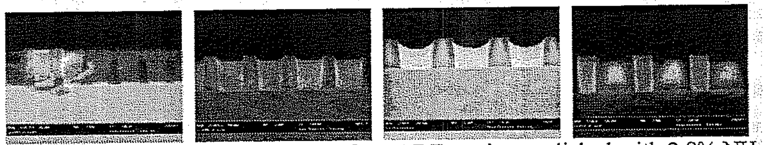

Figure 6. Cross-sectional SEM images of Ge ART sections polished with 2.8% NH_4OH and 4.6% Nalco 2360 in the slurry mix (polished despite vibration).

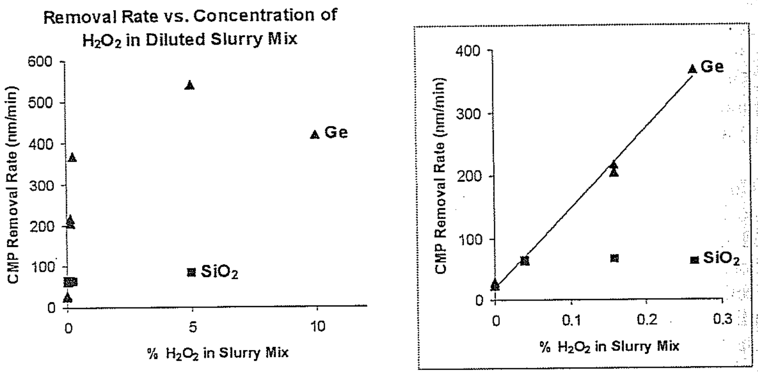

Figure 7. Ge and SiO_2 removal rates determined for slurry mixes containing H_2O_2 additive, with detail of low concentration range at right.

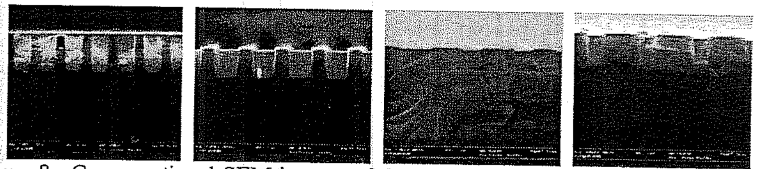

Figure 8. Cross-sectional SEM images of Ge ART sections polished with 0.16% H_2O_2 and 35% Nalco 2360 in the slurry mix.

Selection of Best Slurry Mixture

Figure 9 compares the oxide and Ge removal rates and selectivity determined for various concentrations of these slurry mixes. For CMP of Ge ART, a Ge:SiO_2 polish selectivity of about 5:1 is preferred to prevent significant overpolish (due to difficulty endpointing) or dishing. The addition of H_2O_2 to the diluted slurry worked best, based on the selectivity as well as the SEM results for dishing presented earlier.

In addition to removal rate and selectivity, each of the three diluted slurry-additive combinations was evaluated for concentration of selected metallic elements at the wafer surface post-CMP. The collected data is shown in Figure 10. Data for an oxide CMP process performed on the Strasbaugh CMP is included for comparison to the H_2O_2 and NH_4OH data. NH_4OH added to the slurry mix has the lowest metals levels of the three additives, but NH_4OH does not have the selectivity needed to polish Ge ART.

High metals observed on a wafer after exposure to NaOCl (data at right in Figure 10) clearly show that the levels on a wafer post-CMP could be due to the contamination from the NaOCl solution. The high levels of contaminant metals and dishing observed when using NaOCl additive in the slurry mix are not acceptable for post-CMP device fabrication.

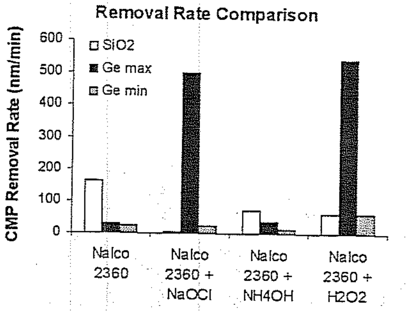

Figure 9. Comparison of Ge and oxide removal rates and selectivities for slurry mixes with the different additive chemicals. Difference in bar heights reflects selectivity for each slurry mix. Minimum Ge RR for a slurry mix and maximum Ge RR for a slurry mix with a different mix ratio are indicated. Ge RR>SiO_2 RR selectivity is possible with NaOCl and H_2O_2, but not with NH_4OH or Nalco 2360 alone. (Graph to show comparison of rates and Ge/SiO_2 selectivity; slurry and additive concentrations are not the same.)

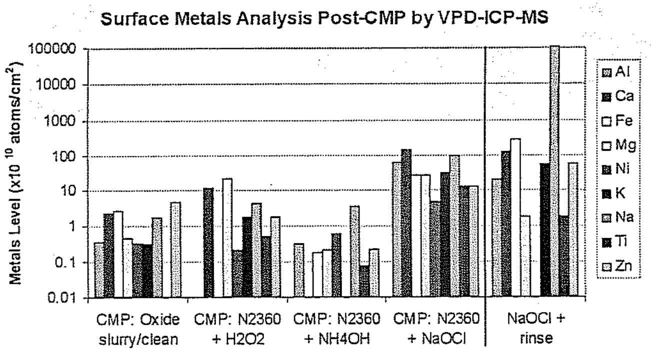

Figure 10. Concentration of selected metallic elements at the wafer surface for diluted slurry-additive combinations post-CMP, with comparative data for an oxide CMP process on the same equipment as the H_2O_2 and NH_4OH data and an evaluation of NaOCl on a wafer without polishing. Data is all from the front-side of the wafer. No data shown for a given metal indicates that the level for that metal was below detection limits of the VPD-ICP-MS analysis.

Some metals levels for polishing with H_2O_2 in the slurry mix are higher than acceptable levels ($5x10^{10}/cm^2$), but this additive had the best performance in coplanar CMP. A short cleaning step was devised to follow the megasonic post-CMP clean, involving a DI water rinse and HF dip. Ge etches slightly in this cleaning step. After the water rinse and HF dip, metals levels were reduced to acceptable levels for samples polished with the H_2O_2-containing slurry mix.

H_2O_2 was the chemical additive to the slurry mix with the best performance in terms of removal rate and selectivity (as seen in Figures 7 and 9), and metals levels post-CMP (Figure 10). Pre-CMP and post-CMP structures are shown in Figure 11. Once the slurry mix chemistry was determined (Nalco 2360, H_2O_2, and DI water), CMP process optimization on the Ge ART samples was possible.

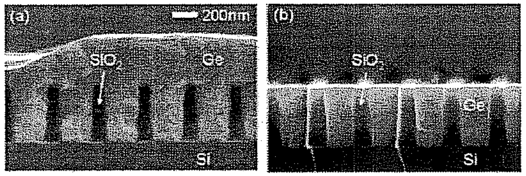

Figure 11. Cross-sectional SEM images of germanium structure before (a) and after (b) CMP with H_2O_2 additive in the slurry mix.

Process Optimization

Concentration of H_2O_2

Although removal rate data for various concentrations of H_2O_2 additive in the slurry mix was already shown above, this was only one of several factors in determining the best concentration of H_2O_2. Pitera warned of pitting when using H_2O_2 (11), and dishing is also a concern if the Ge RR is too high compared to the oxide RR. At the same time, a Ge RR which is too low increases polish time.

Pitting was observed for 5% and 10% H_2O_2 slurry mixes, but decreasing the concentration of H_2O_2 decreased pitting effects. Figure 12 demonstrates pitting observed after CMP using 10% H_2O_2 on a Ge blanket film and 5% H_2O_2 on Ge ART trenches. At the optimized concentration of 0.16% H_2O_2, no pitting of the Ge surface was detected. RMS roughness (of Ge areas in a Ge ART sample) measured by AFM is 0.21nm; the AFM scan is shown in Figure 13.

Dishing also varies with concentration of H_2O_2 in the slurry mix, ranging from unacceptable levels at high concentrations to ~20-50nm for 200-375nm wide Ge ART trenches at 0.16% H_2O_2. Figure 14 illustrates this difference post-CMP, with an SEM image of a significantly dished sample (5% H_2O_2) and a TEM image of polished Ge ART at 0.16% H_2O_2.

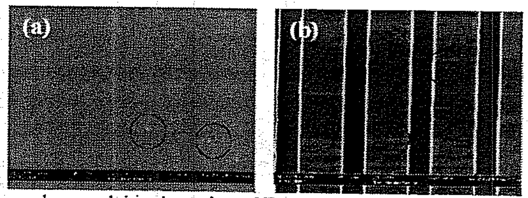

Figure 12. Pitting observed in plan-view SEM for (a) a Ge blanket film polished with 10% H_2O_2 in the slurry mix and (b) an overpolished Ge ART sample, polished with 5% H_2O_2 in the slurry mix. A few defects are circled to assist the eye.

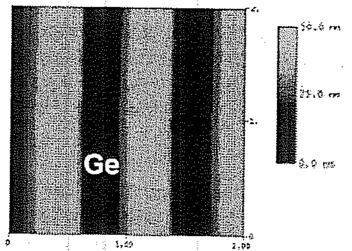

Figure 13. 2μm x 2μm AFM scan of a Ge ART sample polished with 0.16% H_2O_2 in the slurry mix. 30nm of dishing is evident, and RMS roughness measured in the Ge area is 0.21nm. Note that no pitting is seen in the Ge at this concentration of H_2O_2.

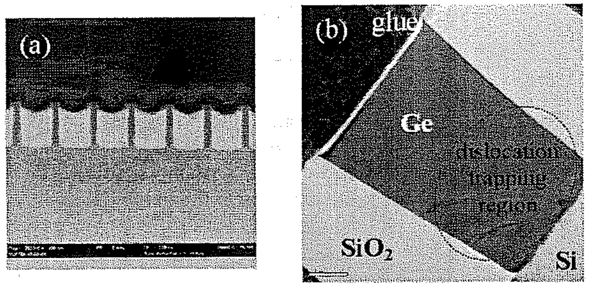

Figure 14. (a) SEM image of significant dishing in Ge ART sample at 5% H_2O_2 (b) TEM image of Ge ART sample polished at 0.16% H_2O_2.

Post-CMP Clean

Most of the samples presented here had a megasonic post-CMP clean. An additional water rinse and HF dip step was added for samples which required reduced surface metals contamination. The megasonic cleaning used diluted SC-1 chemistry for all oxide wafers, but this chemistry was found to etch Ge even at low concentrations, due primarily to H_2O_2. Because of this effect, DI water only was then used in the megasonic clean for all Ge samples (blanket film and Ge ART). This megasonic clean was reasonably effective for slurry particle removal on the Ge samples, except where sample topography prevented slurry from escaping the surface.

Effect of Coalescence on CMP

All of the post-CMP Ge ART samples discussed thus far had pre-CMP structures which are coalesced over the oxide trenches during growth (like Figure 11a). Because of selective Ge growth, each of the patterned areas has a different thickness of coalescence over the trenches, resulting in different times to reach coplanar Ge-SiO_2. However, coalescence may not be necessary if the CMP process can handle uncoalesced Ge ART.

Generally, a CMP process does not reach a reproducible, steady state until after about a minute of polish. For 0.16% H_2O_2 in the slurry mix, polish time for an uncoalesced Ge ART wafer to reach coplanar is typically less than a minute, so controllability of a short process for the uncoalesced Ge ART is uncertain. It may help that the SiO_2 patterning slows the overall polish rate as the structure begins to clear. Initial investigations of the effect of coalescence on Ge ART CMP were concerned primarily with how coalescence might change the clearing behavior of the structures during CMP, so the question of polish controllability was not evaluated.

Analysis of polished 'thin coalesced' and 'uncoalesced' samples focused on evaluating dishing and overpolish as a function of polish time for four different 16mm x 13mm patterned regions (designated A-D). Uncoalesced Ge was grown above the trenches by ~100-200nm; thin coalesced, by ~400-500nm. Combined data for several samples is presented in Figure 15; thin coalesced samples are on the left side of the graph, uncoalesced on the right. Sections A-C had increasing trench widths and corresponding oxide spacing; section D has the same trench width as section A, but with wider oxide spacing. Times listed at the bottom of the chart reflect the polish step; where two times are listed "X+Xsec", two polishes were done on the sample. The original oxide pattern film thickness on this sample was slightly less than 500nm; a 500nm marker line is provided as a reference point in the figure.

The colored bars in Figure 15 represent the thickness of the Ge in the trenches (for a given patterned area and CMP time), measured from the bottom of the oxide patterning to the bottom of any dishing that may have occurred. "Error bars" are used to show the level of the oxide post-CMP. If the error bar ends below the height of the Ge thickness bar, the Ge is underpolished and some Ge remains above the patterned oxide. If the error bar ends above the height of the Ge thickness bar, the oxide height is greater than that of the Ge, and therefore the length of the error bar reflects the amount of dishing in the Ge. Finally, if the end of the error bar lies below the 500nm horizontal line on the graph, the difference between the end of the error bar and the 500nm line reflects how much overpolish occurred for that patterned area on that sample.

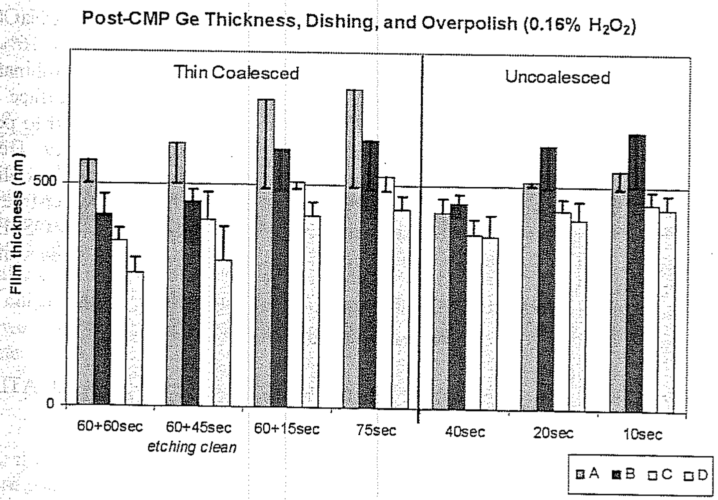

Figure 15. Ge thickness, dishing, and overpolish for thin coalesced and uncoalesced Ge ART wafers polished in 0.16% H_2O_2-containing slurry mix for different times. A-D are the four different patterned areas. See paper text for additional graph interpretation.

An enormous amount can be learned from the data presented in Figure 15. First, comparing the thin coalesced vs. uncoalesced samples, it is interesting to note that the A section clears before the B section in uncoalesced, but the reverse is true for thin coalesced. Also, the amount of overpolish evident in thin coalesced sections C and D (before section A is completely cleared) is much more significant than that observed for the uncoalesced samples when all four sections are cleared. It seems that in order to more effectively clear all four sections without significant overpolish in any of the sections, polishing uncoalesced samples is better. For a thin coalesced sample after two one-minute polishes, section A is not yet cleared, while the film remaining in section D is approaching its dislocation trapping region. On the other hand, if the primary sections of interest for a given sample are C and D, the polish time for an uncoalesced sample would be extraordinarily short, and it would be better to polish from a thin coalesced sample. Only one of the samples tested here used an etching clean (3-5% H_2O_2 in the megasonic post-CMP clean), and it is clear that this sample had more significant dishing than the other samples shown. Finally, some difference can be observed between the two thin coalesced samples with similar polishing times (75 seconds in one polish and 60+15 seconds in two polishes). It seems from these two samples that the ramp-up and ramp-down steps in the CMP do polish a small amount. The data presented in Figure 15 clearly indicate that uncoalesced Ge CMP is possible, and that it provides less variation among the patterned sections, but coalescence may be helpful for some patterned sections.

Conclusion

A CMP process was developed and optimized for planarizing Ge grown in oxide trenches on Si substrates, by the Aspect Ratio Trapping technique. NaOCl, NH_4OH, and H_2O_2 additives were evaluated in diluted Nalco 2360 slurry, for Ge removal rate enhancement. NaOCl and H_2O_2 had high polish selectivity for Ge, but wafers polished with NaOCl had high surface metals contamination levels post-CMP. A 35% Nalco 2360, 0.16% H_2O_2 (30% solution), and DI water slurry mix was determined to have the best combination of selectivity, planarization behavior for Ge ART samples, and low surface metal contamination. This optimized slurry mix and a post-CMP clean were used to polish a variety of coalesced and uncoalesced Ge ART samples to coplanar Ge-SiO_2. Heterointegration by the Aspect Ratio Trapping technique, combined with the optimized CMP process developed here, can be used to create planarized areas of defect-free Ge on a Si wafer. These structures may enable high mobility non-Si channel MOSFETs on silicon substrates, for future generation CMOS logic, and potentially a wide variety of other applications as well.

Acknowledgments

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Micro-Raman Studies on Nickel Germanides formed on (110) crystalline Ge

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Nickel germanides formed on crystalline n-Ge (110) substrate are investigated. By the XRD analysis, Ni_5Ge_3, NiGe, and Ni_2Ge phases are formed sequentially with the increasing annealing temperatures from 300°C to 600°C on n-Ge (110) substrate. NiGe, however, is the only phase observed on (100) substrate at corresponded annealing temperatures. On the other hand, there shows a strong tensile stress in the underlying Ge (110) substrate. The tensile strain may be due to the lattice mismatch between nickel germanides and Ge substrate.

Introduction

The germanium channel metal-oxide-semiconductor filed effect transistors (MOSFETs) have received much attention because it offers 2.8x low field electron-mobility and 4x hole-mobility enhancements over Si [1]. The implement of different substrate orientations such as (110) substrate for the bulk Ge PMOS [2] is also an attractive way to further enhance the drive current. Owing to the recessed $Si_{1-x}Ge_x$ junction technology, currently employed in state-of-the-art CMOSFETs, introducing uniaxially compressive stress in the Si channel, the germano-silicide induced stress is a highly concerned issue to avoid the strain relaxation on underlying $Si_{1-x}Ge_x$ junction [3]. Here, we investigate the Nickel germanidation process induced strain on (110) n-Ge substrate.

Experiments

The n-type Ge substrates (Sb-doped) (110) substrate with resistivity of 0.01~0.1 Ω-cm were used as the starting materials. The (100) substrate orientation is also used for comparison. After cleaning in the dilute Hf solution and followed by DI water rinsing, Nickel blanket thin films (~35 nm) were deposited on the Ge surfaces using the conventional magnetron radio frequency (RF) sputter system at the chamber pressure of $\sim 6\times10^{-6}$ torr and the acceleration power of 80W. The samples were thermally annealed by a conventional rapid thermal annealing (RTA) system at the temperatures ranging from 300°C to 600°C for 1 minute in N_2 ambient subsequently. A micro-Raman system with an Ar^+ laser (λ=488 nm) was used to measure the amount of Nickel germanide induced in-plane strain in the underlying Ge substrate.

Results and Discussion