

Substrate Condition and Metrology Considerations in Poly Gate Doping Implants

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Abstract— The evolution from planar to 3D structures in advanced memory devices has resulted in semiconductor equipment manufacturers facing unprecedented challenges in delivering products that can demonstrate simultaneous compliance to the productivity, reliability and process requirements of their customers. In the field of ion implantation, these challenges are driven by: (i) the increasing prevalence of hard mask and removal of PR stripping process and (ii) the transition from the use of implants in dopant application to that of materials modification. These have resulted in large reductions in both the particle size and number density that can be tolerated from implant steps.

One area where these issues have proven challenging is that of contact engineering. Low energy phosphorus implants are used to improve the contact resistivity of poly Si contact. This is critical for the read/write time of the storage node capacitor in DRAM operation. As devices shrink further, the thickness of the poly gate in the peripheral transistors become as low as a few hundred Å. This results in a phosphorus implant requirement of ~1keV. Depletion in the poly Si gate requires a few keV implant energy for poly doping for both NMOS and PMOS. In order to maintain proper gate operation, gate doping requires around E15 doses. This places a large amount of implanted phosphorus at or near the surface of the wafer.

In this paper, a phenomenon is described where the magnitude of surface particles arising from phosphorus implants is a function of the reaction between implanted phosphorus and ambient atmosphere. Using SEM/EDX, spatial and morphological descriptors of the defect types arising from these reactions have been classified. The implications of these results will be discussed from both a process perspective, in terms of accumulated dose and implant energy, and a time-based effect whereby defects grow over time both in number and size. Mitigation paths for particle metrology are proposed, and guidelines for Fab operators in terms of material storage and particle monitoring protocols described, in particular the criticality of time to measurement and maximum implanted dose.

Keywords— *defect growth mechanism; poly gate doping; metrology*

I. INTRODUCTION

Defect requirements for semiconductor equipment continue to evolve and are now no longer hygiene factors but rather points of competitive differentiation, both in terms of particle adders and energetic or surface metallic contamination. Advanced photolithography and track tools now require measurement of particles down to 15nm, necessitating improved metrology capabilities. While ion implantation lags other key nodes of processing in terms of absolute particle level requirements [1], recent evolution of device structures and the increasing use of implant for

materials modification rather than conventional doping has required device manufacturers to make large changes in either minimum particle size measured, particle upper control limit or both in order to maintain device yield and performance requirements.

Making these large defect requirements changes even more difficult for both device manufacturers and implant equipment vendors to attain is that, increasingly, the use of benign particle monitoring recipes, such as a P/30keV/5E14 recipe at low beam current, which for many fabs was the particle monitor recipe (PMON) of choice, has been supplanted by recipes which are more representative of production. This change is predicated by the fact that particle performance in ion implantation is highly process specific, and hence good particle performance for a benign recipe only tells the user that the equipment is not suffering from a gross particle issue, and tells nothing about the actual performance of a production recipe.

When high dose production recipes are run as PMON recipes on high current ion implanters, in addition to surface defects which may be added by the processing, other factors arise which can contribute to the measured particle performance. These include surface damage, which appear as changes in the haze maps on the particle measuring tool, and may be falsely identified as particle excursions if care is not applied in tailoring of the recipe on the metrology tool. However for some species there are additional challenges that have not been well quantified, resulting in apparent large variability in PMON data from tools that are running these monitors. In this paper one such excursion type is considered, arising from monitoring of the Poly doping P implant in DRAM manufacturing.

II. TECHNOLOGY DRIVERS

Ultra shallow implant requirements for coming technology nodes place restrictions on device performance and yield management. This is driven by the need of precise dopant placement with high level of purity, combined with extremely low defect densities. At the same time increasing implant doses at lower energies, and shallower implants of multiple species, combine to make high current implant a significant challenge. The expansion of ion implant applications from traditional electrical doping to materials modifications implants, combined with introduction of new materials and chemistry for patterning, deposition, etch and cleaning result in more complex interactions between implant and neighboring technology. New 3D structures have been utilized in various devices such as FinFET, DRAM capacitors and 3D NAND Flash high aspect ratio stacking, and these add new aspects to check for optimized integration flow.

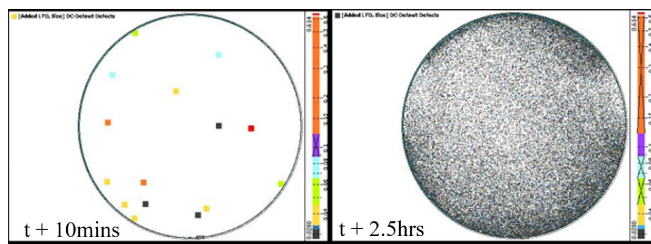


Fig. 1. Effect of delay on measured particle map

For DRAM devices, low energy high dose implantation historically has been applied across the transistor structure with different goals. For shallow junction formation these include precise dose control, across wafer uniformity (afforded by beam angle control), optimization of co-implant and damage engineering. For materials modification implants such as contact implant to Si and/or poly-Si, cross contamination, energy contamination and optimization of dose rate control have been required to meet device node requirements. Defect control including understanding particle generation, monitoring and control as well as productivity improvements are strongly linked to device requirements and are a key component of hardware/software development in implanter technology.

Modern high current ion implanters, such as the Axcelis Purion H2™, provide enhanced productivity for the high dose Phosphorus implants required for contact engineering. The productivity limit is determined by the beam current – as implant energies drop so to do the available beam currents, as these beams are space charge limited and hence transport through the final field free region to the substrate surface determines the maximum beam current available. Injecting larger current of beam into the final energy filter results in more beam current but also larger beams. Larger beams can interact with more surfaces in the process chamber and result in particle excursions.

While working to minimize these beam-surface interactions at enhanced beam currents, it was discovered that particle excursions observed in the Fab environment were not present in the Lab study. The causes of this effect will be discussed later in this paper, however we contend that the controllable differences (implanter recipe; substrate type and condition), while important for good particle performance, do not explain the lab to fab gap.

III. EXPERIMENTAL STUDY

All implants were undertaken on an Axcelis Technologies Purion H2™ high current ion implanter and all particle measurements in this study were conducted on a KLA-Tencor SP5 SurfScan™ system using particle grade p-type wafers at Axcelis Technologies in Beverly, MA. The Axcelis facility is a class 10 cleanroom climate controlled to maintain 40% Relative Humidity (RH). All SEM-EDX data were gathered at Albany Nanotech, SUNY, on a KLA-Tencor eDR7110™.

This study was initiated by two separate observations arising from issues in customer sites. Firstly, the probability of a particle excursion as monitored by bare wafer was a function of the cumulative dose in the wafer, and secondly delays in measurement resulted in anomalously high particle readings. While the former result may be anticipated from a consideration of substrate damage, the latter result was

unexpected. This is illustrated in Fig. 1., which shows the same wafer measured immediately after implant and then again after 2.5 hours. Note that the authors verified that this was not an artifact induced by the laser fluence of the metrology tool by running a separate experiment whereby the wafer was measured multiple times in quick succession – in this instance little change in the wafer map is observed.

Particle maps were taken in Defect Source Analysis (DSA) mode – the map shows the net adders from the process. The haze maps, not shown, indicate that the wafers have a homogeneous damage profile. A consideration of the particle maps reveal some information. The original particle adders are randomly spaced spatially and have a broad distribution of sizes. When we consider the measurement taken after 2.5 hours, the first thing that is obvious is that (aside from the $\sim 1E5$ additional particles now present) there are far more particles at the edge of the wafer than at the centre. The bin size distribution data are very unusual for an implant, with a saturation in the 28-32nm bin split. From this result, it was decided to analyze this phenomenon as a function of energy, dose and measurement delay.

The precise energy and dose of the implants under consideration are proprietary. This study considers Low Energy High Dose Phosphorus (LEHDP) implants to be those with an upper ion energy bound of 5keV and a lower energy bound of 1keV, and with implanted dose of $> 3E15$ atoms. Modern ion implanters run in production at around 30mA beam current for a typical low energy Phosphorus implant and so an implant time of around 1.5 minutes per wafer may be considered typical for these experiments. Due to the dose, the implants are not mechanically limited and run at a factor of 10 below the 500 wph mechanical limit – as a result, wafers spend a considerable amount of time staged awaiting implant.

A series of implants were then executed as follows: Prime p-type Si wafers were used so as not to risk contamination of the study by surface damage from the use of n-type wafers or reclaims. Wafers were implanted 1keV, 3keV and 5keV at multiples of $5E15$ dose to simulate current P-gate implant steps in DRAM. Wafers were stored in a FOUP in a class 10 clean room for varying periods of time prior to particle measurement. Once all wafers were measured, these were then double bagged, vacuum sealed and sent for SEM/EDX analysis.

IV. ANALYSIS

Let us first consider the effect of dose. Wafers were implanted at three energies (1keV, 3keV and 5keV) and at multiples of mid- $E15$ dose. Ten wafers were used for each condition. Baseline particles for the first implant were < 20 adders per pass at $> 32nm$. The magnitude of the observed excursion at high dose is variable implant to implant and is always at least 2 orders of magnitude above the baseline level. Based on our study, the max implant number is the number of implants below that which the first excursion was observed. Taking a simple product of energy and natural logarithm of dose yields a guideline for this maximum implant number, which is shown in Fig. 2.

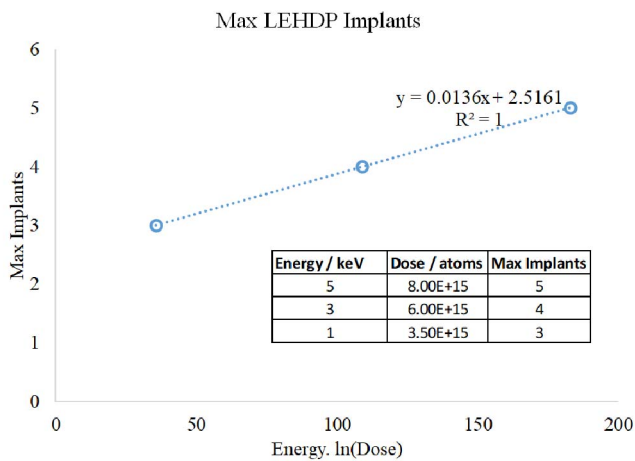


Fig. 2. Max implants as a function of energy and dose

The proposed mechanism for this observed issue is the large amount of surface Phosphorus resulting from the implant. Typical LEHDP SIMS profiles are shown in Fig. 3 (the three traces represent different tool configurations). As the implant energy reduces, and/or the dose increases, the magnitude of this surface concentration will rise. Further factors known to occur which could conflate this process are the segregation of Phosphorus at the Si-SiO₂ interface and migration of the implanted Phosphorus back to the surface.

Secondly, let us consider the time dependence. Initial observations of the phenomenon had occurred when wafers that had been implanted, post measured showing very low adder counts, and then re-measured the next morning, showed >1e3 particles on the surface. These wafers had been left in a non-purged but sealed FOUP at ambient in the class ten clean room. It was found that by double bagging and sealing the wafers the probability of elevated particle on re-measurement could be reduced but not eliminated. Even at ~ 2hours at 40% RH there was sufficient reaction with ambient air to result in large counts on remeasurement. Below 1 hour no elevation was observed. This has led us to conclude that a maximum measurement delay of 90mins from implant is advisable for LEHDP implants, however as this study did not determine the impact of exposure to different RH levels this may be a function of RH. Typical spec for semiconductor manufacturing equipment is an RH of 40-45%, balancing avoiding both electrostatic discharge and condensation on cooled surfaces. Many Fabs typically operate at or below the lower end of this range – measurement on weather stations attached to many tools read 36-40% RH. With the increasing prevalence of N₂-purged FOUPs it is likely that this time to measurement can be extended, and this is proposed for further study.

Analysis of the particles themselves yielded the following information: From the SurfScan™ data, defects arising on the wafer from small numbers of implants are random in location and are in general < 15 adders / pass at > 32nm. The lack of characteristic spatial patterns indicate that they do not arise from a mechanical source or a high voltage discharge event such as an insulator breakdown or arcing between graphite electrodes. It is postulated that the majority of particles in LEHDP operation arise from beam clipping on graphite apertures in the near wafer environment. Since the incident ion energy is very low, the

likely particle source is not the graphite itself but beam interactions with deposited material on these apertures.

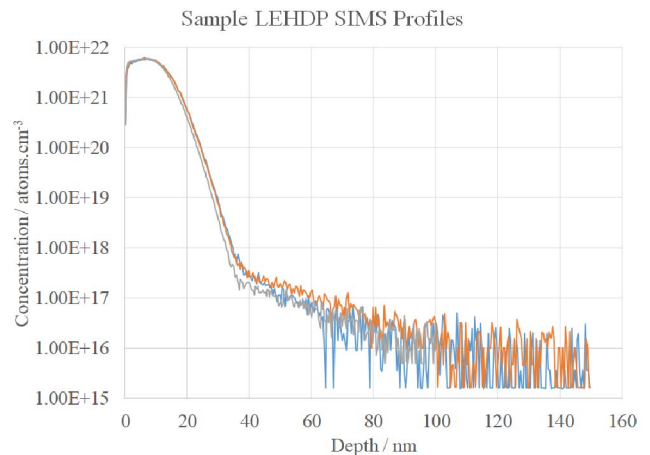


Fig. 3. Typical LEHDP SIMS profiles (three h/w configurations shown)

The particle size distribution indicates that this phenomenon may have been occurring for some time in production. It is only with the transition to smaller particle sizes in offline metrology (minimum bin size at 45nm or below) does the issue become noticeable. Due to the large variation in the amount of time it can take a PMON wafer to get processed in a large scale Fab (between 30mins and 6 hours is typical) the time dependent nature of the issue can lead to false PMON excursions being flagged. This is especially true when Fabs are in start-up phase – there is typically a large demand on a small number of metrology tools to qualify each step of the process, resulting in large backups at the tools and extended exposure time of the wafers prior to measurement. Further, wafers are often re-used multiple times during qualification leading also to false positives caused by overdosing. Queue time after pre-measurement becomes a concern – historically post counts from the last time a PMON was measured are used as the pre-counts for the next measurement, even if that measurement is many hours or days afterwards. As we have seen with the LEHDP implants, this leads to excursions.

SEM/EDX was then employed to determine the morphology and elemental constitution of the particles. Since surface characterization after implant could not be completed in real time, it was practical to analyze wafers as a function of dose rather than as a function of time to measurement. Fig. 4 presents a cross section of three types of particles observed.

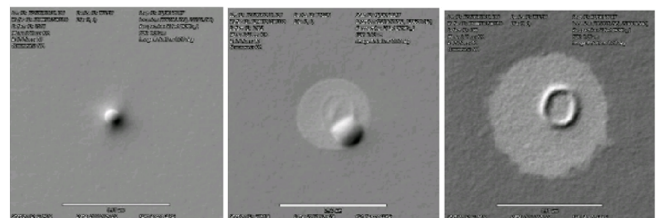


Fig. 4. Different LEHDP particle morphologies (left to right: “Spherical Blob”; “Blob with stain”; “Ring with Stain”)

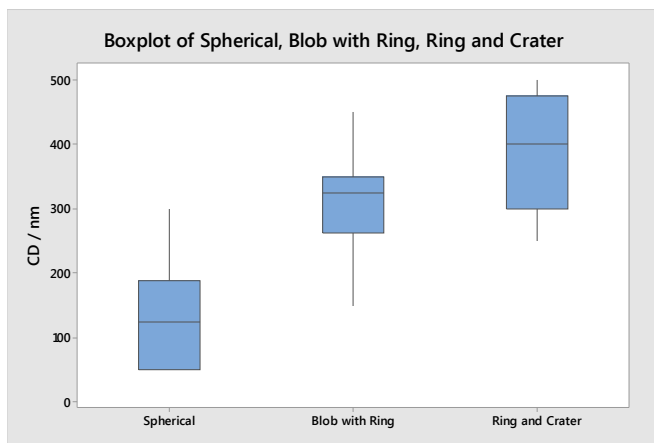


Fig 5. Size distribution of LEHDP particle types

Subjectively, these have been classified into 5 types. The smallest particles are spherical in morphology – those with a “half melted” structure are larger, and largest of all appear as stains. Fig. 5 shows the size distribution observed when sampling 100 particles on 10 wafers implanted with 1x LEHDP implants. The EDX data are shown in Fig. 6 – the left plot is a typical EDX of a “spherical” particle and the right plot is a plot of a ring/stain particle. The primary peaks are Si, C and O. Phosphorus only appears as a small signal for the spherical particles but is absent from the stains, indicating that the dopant has reacted with ambient to form a volatile substance such as H_3PO_4 . When those wafers with 5x dose were probed, all particles had a flattened spherical appearance and all contained P signals, indicating saturation on the wafer surface.

V. DISCUSSION & FINDINGS

Several relevant studies on similar phenomena exist in the literature. In a paper by Borot et al. in 2006 [2], surface effects of high dose As and P in Epi and Poly Si were examined, following CVD growth of these films. They observed large amounts of surface ad-atoms for P and As, which were readily removed through cleaning. A more pertinent study looked at surface bumps or swelling due to Phosphorus dose at the surface [3], which showed that surface swelling at the Si:SiO₂ interface results in a hemispherical bump that can be measured as a particle. The size of these defects were on the order of 200-300nm.

An alternate interpretation was offered by Ianovitch [4], wherein his study showed the formation of crystallites of dopant at the surface which would also manifest as particles. Note that the SEM/EDX studies conducted in our paper did not appear to show crystals but rather spherical blobs, more in line with the paper of Khandekar et al. [3].

The two principal findings of this investigation are as follows: At typical humidity levels observed in semiconductor fabrication facilities a time of 2 hours after implant is sufficient to result in a reaction between surface Phosphorus and moisture, resulting in wafer saturation. Furthermore, the max number of implants is critical even if the wafer on initial measurement looks clean. Suggested mitigation techniques include use of purged FOUPs and keeping the wafers under dry Nitrogen. A systematic study involving controlling the time between implant and

SEM/EDX measurement is required to unambiguously determine any particle evolution over time in the critical first 2 hours after implant.

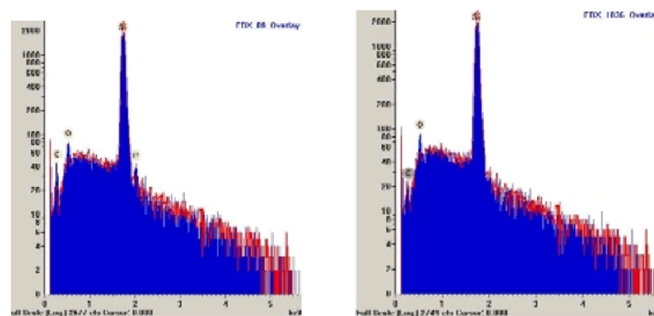


Fig. 6. Elemental disposition of LEHDP Particles

Based on the findings herein, the following conditions are recommended to minimize the risk of false particle findings due to high surface dose of Phosphorus:

- Max number of implants for LEHDP PMON wafer is a function of energy and dose - e.g. 3 for P/1keV/3e15
- Max delay between implant and particle reading - particle measurement must occur as soon as possible after implant
- Max delay between pre-reading and implant – all PMON must have a new pre-reading within 30minutes of implant and not rely on last post-reading of that same PMON wafer
- Max starting adds for PMON wafer – recommend < 3x UCL compliance
- All PMON FOUPs must contain at least 1 Control wafer – all PMON FOUPs and dummy FOUPs to have 2 control wafers (slot 1 and slot 25)

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