Paul Williams and Xie Shao, "Process Considerations for Organic Bottom Anti-Reflective Coating [BARC] Optimization for Front-End and Back-End-of-Line Integration," *SEMICON China 2003 SEMI Technology Symposium*, March 12-14, 2003, pp. 229 – 238.

As presented at the SEMICON China 2003 SEMI Technology Symposium on March 12-14, 2003, in the Shanghai New International Expo Center, Pudong, Shanghai, China.

Process Considerations for Organic Bottom Anti-Reflective Coating [BARC] Optimization for Front-End and Back-End-Of-Line Integration.

Paul Williams [1], and Xie Shao [2]

1 Brewer Science Asia Ltd.
1902A, The Centrium, 60 Wyndham Street, Central, Hong Kong.

2 Brewer Science, Inc.,
2401 Brewer Drive, Rolla, MO 65401, USA.

Biography

Paul Williams received his B.Sc. in Physics from Nottingham University and his Ph.D. on hot electron transport in GaAs devices from the University of Wales, Cardiff. After joining Brewer Science in Europe as an Applications Engineer he worked at Brewer Science USA as the ARC® Marketing Manager for Asia. His current position is the Business Manager for Brewer Science Asia Ltd. in Hong Kong.

Xie Shao received her Ph.D. in organic chemistry at the University of Basel, Switzerland, followed by two years postdoctoral experience at the Ciba-Geigy AG Department of Pharmaceutical research, and one year postdoctoral in SUNY (State University of New York) at Buffalo, Department of medicinal chemistry. She joined Brewer Science in 1993 as a Sr. Research Associate. Her current position is product manager responsible for DUV BARC products.

Abstract

Bottom anti-reflective coatings [BARC] are now routinely used in semiconductor manufacturing to enable advanced lithography on, and patterning of, reflective substrates. For successful implementation into IC manufacturing lines, large and robust process windows must be defined. This article will describe the processing and material characteristics of BARC with reference to three applications where the introduction of a BARC layer is becoming essential. These are (i) the definition of the initial critical layers, (ii) the introduction of thin resist implant processes and (iii) the integration of copper interconnect to Back-End-Of-Line [BEOL] metalization.

As with advanced photoresist, the requirements for BARC material is also becoming more demanding. As photoresists become thinner, BARCs are also required to be thinner and have increased etch rate compared to the photoresist. In addition to process optimization, particular attention will be given to fast etch rate conformal BARCs for sub 0.13 µm KrF and ArF manufacturing. Also wet patterning processing, where the BARC open etch step is eliminated since the BARC patterning occurs simultaneously in the resist develop step. For BEOL, the BARC requirements can be different, as trench and via structures require total planarization. In addition etch block is also necessary. Each of these material and process steps will be described.

1. Introduction

The theoretical characteristics required for an anti-reflective coating, and initial material and chemical platform considerations when designing a BARC have been described previously [1,2]. Based on recent developments, this article introduces the reader to the process and material characteristics required for a number of device patterning applications. The process optimization methodology is described for front-end applications: i.e. the poly gate application and active area and contact. This will include photo and BARC open etch optimization. The emerging technology of thin resist ion implant with wet patterning BARC will be discussed in detail. Finally, due to the aggressive move to low k inter layer dielectric [ILD] and Cu interconnect, BARC coating requirements, BARC open etch and substrate etch requirements for Dual Damascene via-first technology is also discussed. The article concludes with a summary and a step-by-step review for lithography and etch engineers considering organic BARC technology for the first time.

2. Optimization considerations for FEOL.

Before discussing the particular applications associated with device manufacturing it is necessary to consider the lithographic and substrate process as a whole. For this reason we will discuss not only lithography considerations but also implant and etch related applications when processing with BARC technology.

2.1. Exposure set-up

Initial process set-up involves characterizing the overlapping exposure latitude [OEL] and depth of focus [DOF] usually defined as CD±10% across all pitch. Initially this involves setting the resist and BARC thickness recommended by the vendor, and performing sigma optimization for fixed NA. At the optimal sigma, an NA optimization is performed by conducting DOF and OEL measurements [3,4]. In general, BARC optimization occurs after the photoresist set-up, therefore no process conditions for resist or develop optimization will be discussed as it is outside the scope of this article.

2.2 Optimization of the resist profile

In theory, the lithographic performance is optimal on perfectly flat non-reflective substrates. However, due to the physical characteristics of the develop process, bleaching within the resist and the non-transparent nature of photoresist, it is sometimes necessary to allow some reflection back from the substrate. This is a popular technique at i-line to enable better DOF performance of photoresist on flat substrates. The resist profile can be affected by the residual reflectivity returning from the substrate back into the resist flank, as seen in figure 1.

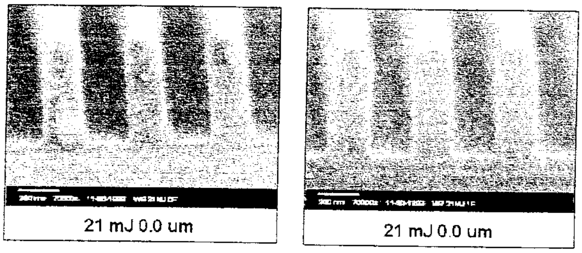

Figure 1. Profiles of DUV BARC on resist. 1a BARC thickness of 600Å with 1% reflectivity. 1b BARC thickness of 800Å with 4% reflectivity.

The baseline reflectivity should not be so large that interference effects such as standing waves occur [5].

In addition to the planarization considerations from the BARC, the photoresist coated on top of the BARC will also planarize any residual local depressions in the BARC surface. Performing lithography on such surfaces represents the true challenge encountered by lithographers today.

After the optical set-up, BARC/resist lithography set-up is necessary. The process comprises of profile optimization and CD dispersion minimization. In addition to the BARC thickness, for KrF and ArF, acid diffusion between the resist and BARC plays a major role in profile definition and adhesion. Due to the mobility of acid generated during the exposure process, and diffusion during post exposure bake, [PEB], both chemical and process matching between the BARC and photoresist is essential.

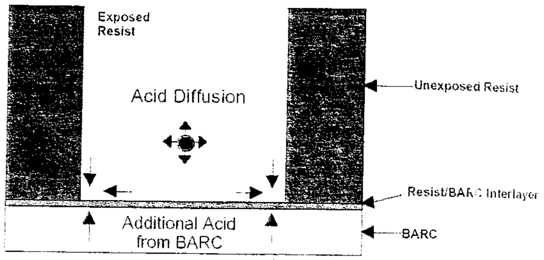

Figure 2. A schematic representing the diffusion of acid between the resist and BARC [5].

The effect of acid concentration at the interface has been shown to effect the profile of the resist on the BARC. By optimizing the BARC bake temperature it is possible to control the degree of densification of the film and acid penetration into and out of the BARC film, shown schematically in figure 2. Thus the BARC bake temperature [6], and the acidity of the cross-linking system and polymers within the BARC platform have been tailored for perfect resist/BARC matching [7] shown in figure 3.

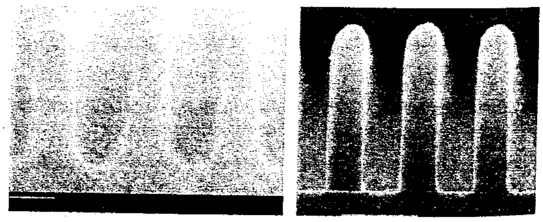

Figure 3. Profile improvement due to modification of the BARC acidity resulting in excellent matching. 3a, mis-match system, 3b optimized BARC to the resist.

The final part of the lithography optimization involves judicious choice of BARC and photoresist. It should be noted, for simplicity, we assume in the following discussion for the swing curve incident illumination is constant [optimized from the initial set-up]. Therefore shifts in the swing position and amplitude are related to the incoupling within the resist and BARC and their combined thickness variation in relation to the underlying topography.

3. Applications

The required BARC properties differ according to the application, as is explained in the following three examples. These are polysilicon gate [opaque substrate litho and etch]; ion implantation [opaque or transparent litho with wet patterning BARC]; and Dual Damascene [via fill and substrate etch].

3.1 Poly gate

3.1.1 Resist/BARC thickness variation.

Due to the nature of the isolation process, it is necessary to consider the coating behavior and thickness variation of the resist and BARC not only globally but also locally. These are highly dependent on the pitch and height of isolation.

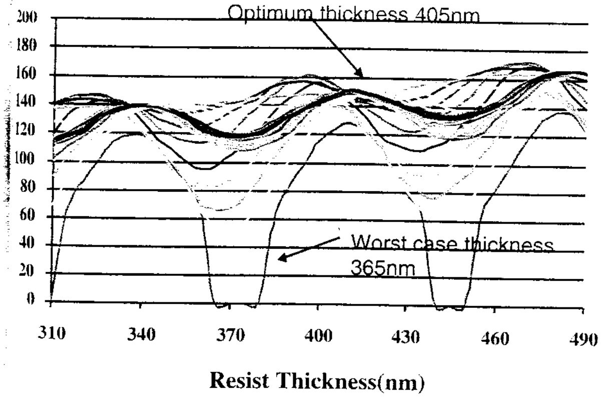

Figure 4. Critical Dimension dispersion for a range of BARC thickness from 0 to 150 nm thick. For a nominal CD of 0.15 μm

By coating the surface with organic BARC, the reflectivity back into the resist is highly dependent on the thickness of the organic BARC. This also relates to the planarizing properties of the BARC.

The CD dispersion associated with different resist and BARC thickness interactions is shown in figure 4. It is clear there are optimal combinations of resist thickness [with BARC] where the dispersion is minimized. At these points the variation of CD is relatively insensitive to BARC thickness variation. Each line represents a different thickness of BARC and can simply demonstrate the effect of planarization of topography where BARC thickness varies.

Plotted in a slightly different format, figure 5 demonstrates the dramatic effect of choosing the optimal and worst-case resist thickness for poly gate applications over topography. If the best case resist thickness is chosen it is seen the CD control specification is achieved with very little BARC thickness. However, if the incorrect resist thickness is chosen, relatively thick BARC is needed to achieve tight CD control after litho

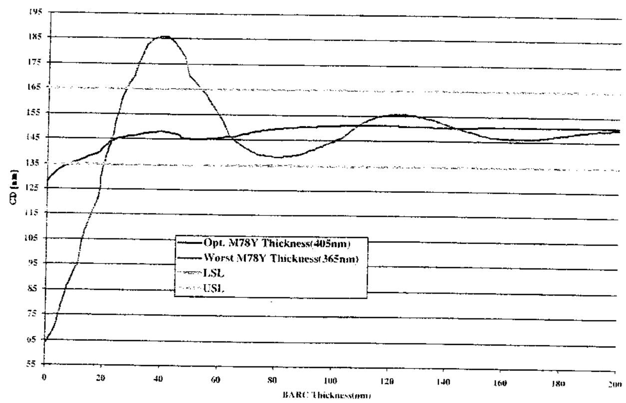

Figure 5. The simulated CD dispersion as a function of BARC thickness for a 0.15 μm poly gate structure. Two resist thickness have been shown representing the best-case and worst-case.

The efficiency of planarization depends on the thickness of the coating, the shrinkage of the polymer solution, the flow properties of the polymer during the coat cycle and pattern density of the surface [8].

BARCs are either inorganic or organic in nature. Inorganic BARCs are conformaly coated utilizing CVD or sputtering techniques, whereas organic BARCs are currently spin coated and, depending on their composition, have either conformal or planar coating. However, due to the nature of spin coating, it is not possible to achieve 100% conformality. A schematic diagram representing a partially conformal and planar spin coated BARC is shown in figure 6.

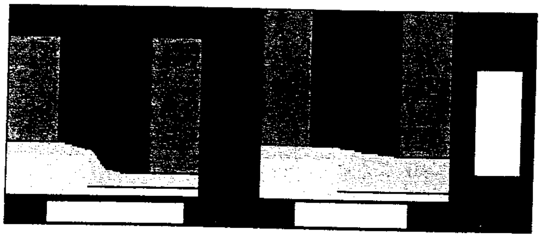

Figure 6 represents the different coating behavior over steep topography for a) conformal coating BARC, and b) planarizing BARC.

To optimize the BARC process over topography, IMEC introduced the concept of topography swing curves [9] to monitor areas throughout the device to choose the best BARC/resist combination. Unsurprisingly the tightest CD control is obtained within photo by the implementation of an optimized resist process on a fully planarizing BARC. However, we must consider the BARC patterning process.

3.1.2 BARC patterning optimization.

Two of the methods used to achieve improved resolution are reduction of resist thickness and the introduction of BARC into the process.

In addition to improve resolution, BARC technology is introduced to improve CD control resulting in greater demands for increased etch rate and selectivity to the masking photoresist, while additional demands to reduce the thickness of the BARC [for poly gate applications] to minimize etch time.

It is shown in figure 7 how successive generations of Brewer Science BARCs have increased etch selectivity to photoresist. It can also be seen that BARCs specifically designed for advanced KrF lithography [sub 0.14 μm] have very high and tunable etch rates, increased conformality and are used at lower thickness. Typical BARC processes for organic BARC etching include O_2. However, due to the erosion of organic photoresist, novel polymers have been used to ensure high selectivity. In addition, the gas chemistry is also tailored to polymerize the resist thus reducing resist erosion.

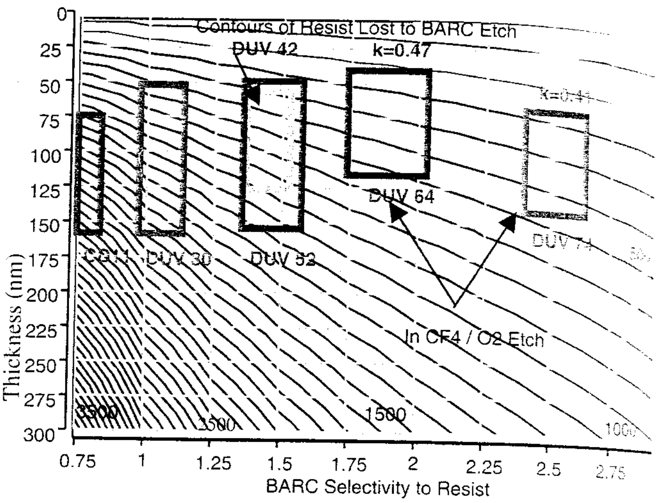

Figure 7. Contour plot representing the increase in etch selectivity of BARC to photoresist for successive generations.

Typical gas chemistry for BARC open in a high density, low pressure etch system is HBr/O_2 which generates an etch rate of 3-500 nm/minute. By modifying the gas chemistry [e.g. $CF_4/HBr/O_2$ or Cl_2/O_2] it is possible to improve CD uniformity and etch rate but with reduced selectivity to poly [using Cl_2] and Oxide [using CF_4] [10].

When IC manufacturers move from benchmarking to manufacturing, due to the reduced resist thickness, it has been necessary to use BARCs with increased etch rate. This can be seen with two ArF BARCs from Brewer Science; ARC25 introduced for benchmarking, and the original industry standard for manufacturing in Asia: ARC29A.

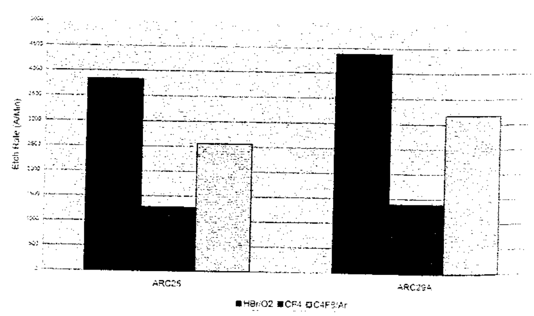

Figure 8. Increase in etch rate between original benchmark BARCs used for equipment qualification, and ArF BARC used in manufacturing.

The final part of BARC etch optimization is the reduction of any isolated to dense line bias remaining after the photo/BARC open etch step. It has been shown for high density low pressure etch systems that it is possible to tune the BARC open etch process to compensate for the iso-dense bias in either the substrate etch or after lithography. For high density systems, such as toroidal coupled plasma [TCP], there are two powered plates; the source or TCP [Ws] and the bias power [Wb]. By modifying this ratio [Ws/Wb] it is possible to modify the bias between isolated and dense lines. This mechanism can be very effective for foundry facilities [11]. When facilities use older equipment with high pressure, low density systems, due to the absence of the TCP or source power, it is possible to optimize the bias power and the gas chemistry i.e. the ratio between the oxygen and polymerizing gas to tune the iso-dense bias [12].

In addition, the etch selectivity between BARC and resist can be increased by performing a UV cure. Here the substrate is heated while being irradiated by UV light. This has the effect of "softening" the BARC and increasing the degree of cross linking of the positive tone photoresist [13,14].

As IC manufacturing companies continue to drive down the cost of ownership of each process, many are now evaluating the removal of the BARC open etch step by implementing a developer soluble BARC process. This has been common practice at g-line and i-line for many years [e.g.15-16], but with the introduction of new KrF wet patterning IMBARC™ from Brewer Science this is now a major consideration for 0.25 μm and 0.18 μm gate manufacturing.

3.2 Active area , contact and via applications.

3.2.1 Resist/BARC thickness optimization.

Many of the considerations for process set-up such as NA/Sigma and resist profile have already been covered. For transparent substrates, reflectivity minimum [a term used for polysilicon and metal applications] has little meaning. This is because different thickness of underlying transparent stack introduce thin film interference effects with the incident light, resulting in a series of reflectivity curves each one slightly "out of phase" with the next, forming the tornado plot described previously [2] and shown later in figures 12 and 16.

For lithography process optimization incorporating a BARC, we must look at the average reflectivity over the range of thickness variation within the oxide/nitride stack. At contact or via, underlying thickness variation within the substrate can be considerable since [in general], a form of planarization from either etch-back or chemical mechanical polishing [CMP] has occurred There is also the problem of topography across the transparent substrate.

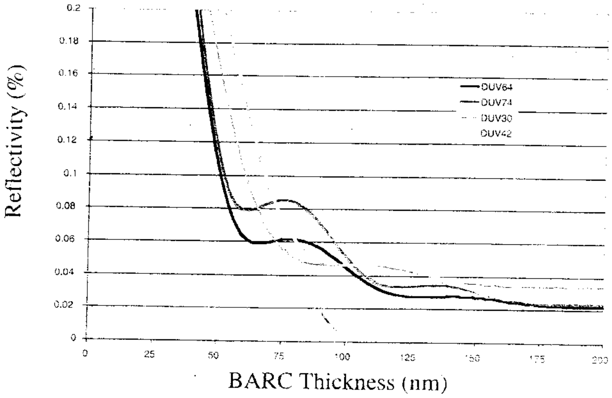

Figure 9. Maximum reflectivity over 250 nm variation of oxide thickness is plotted for four BARCs. DUV64 and DUV74 have high n value [>2].

The "envelope" of maximum reflectivity as a function of organic BARC thickness coated over a planar surface with differing oxide thickness is represented in figure 9. The dramatic reduction in the thickness of BARC needed to bring the baseline reflectivity below 4% is demonstrated [100nm compared to 140nm for low n BARC].

High n organic BARCs offer an advantage over conventional BARCs, with lower n, enabling lower thickness BARCs to be used on oxide at the "choke point" where the baseline reflectivity drops significantly. For conventional BARCs [n~1.5] a thickness of approximately 140 nm of BARC is required to reach this point, whereas for the new generation [n~2], this is achieved at around 80-100 nm. The reduction in thickness will of course contribute to improved throughput during etch..

For higher throughput and lower cost of ownership, the BARC etch step is eliminated, by implementing wet patterning BARC technology. The BARC bake process margin is larger for dark field applications as undercut is acceptable without the loss of resist for the substrate etch, Figure 10 shows 0.22μm pattern with no undercut.

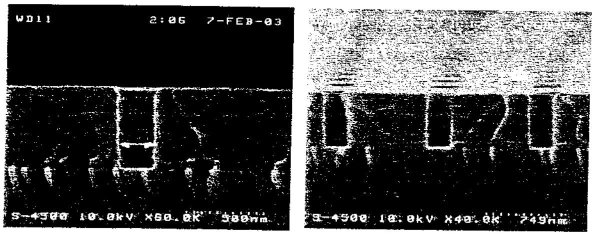

Figure 10. A 0.22 μm contact holes for a) isolated and b) Semi-dense pattern with wet patterned KrF BARC. Dark field contact hole masks can tolerate a larger degree of BARC undercut without resist loss, thus widening the bake window [2].

It has been demonstrated that undercut pattern is not transferred into the substrate during etch. Feature shrink only occurs if BARC footing is present [15].

3.3 Ion implantation with wet patterning BARC.

3.3.1 BARC bake optimization and resist matching.

The bake window for wet patterning BARC technology has been presented previously [2]. The solubility of the BARC in aqueous developer is controlled by the BARC cure temperature. Historically this technology has been implemented for metal and poly applications. Recently with advanced Bi-CMOS applications, problems with defining the emitter open processes have been resolved with the introduction of wet patterning BARC. Due to the chemical amplification of the photoresist, and the smaller CD requirements, resist/BARC matching is essential for wet patterning KrF technology.

As device complexity has increased, process development in ion implantation now requires ultra shallow doping of polysilicon and numerous masked levels. These include source/drain formation, threshold voltage tuning, lightly doped drain [LDD] and other extension implants. Other large angle tilt implant technology is also being used to simultaneously minimize short channel effects and improve transconductance [17,18].

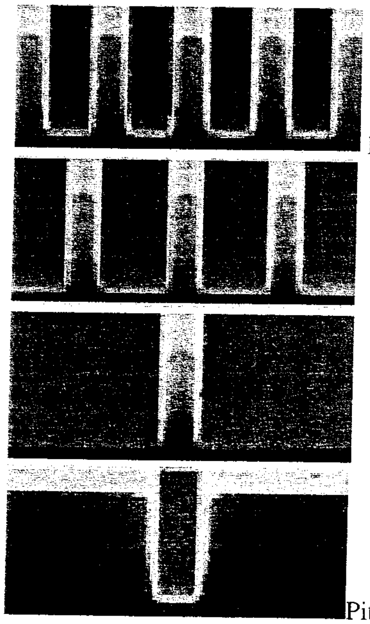

Figure 11. Perfect matching is demonstrated between photoresist and wet patterned BARC. TOK TDUR-P338 with IMBARC™10-7 for 180nm dense, semi-dense and isolated features [19]. The BARC cure temperature is 175°C for 60 seconds.

Here, the aspect ratio of the defined space to the combined resist/BARC thickness is critical. In addition, no undercut of the BARC is also imperative due to shadow masking. Figure 11 shows such vertical profiles necessary for this technology. Since a number of these implants occur through combinations of different reflectivity substrate, and no BARC open etch step is necessary, thicker BARC films are acceptable [contributing to the total thickness of the masking stencil]. It is possible to reduce the resist thickness to achieve higher resolution [20].

Since a number of implant layers comprise of transparent layers and the BARC thickness contributes to the aspect ratio, optimal reflectance/thickness requirements are essential. Figure 12 shows the typical thickness of BARC needed to reduce the reflectance to below 6%. It is observed, the choke point occurs at around 70nm over 300nm of oxide or nitride variation. This is then introduced into the calculation of the best resist thickness and total mask height for the application.

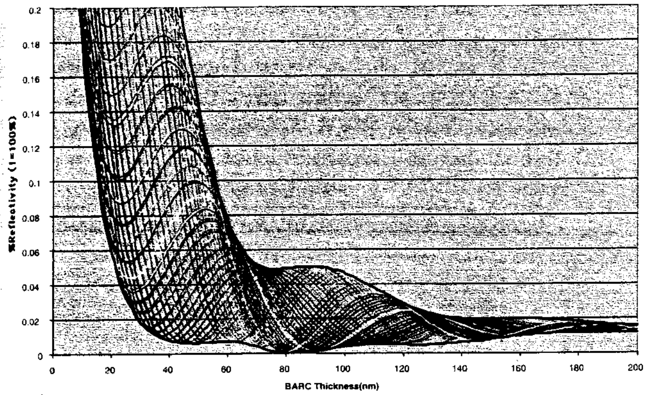

Figure 12. IMBARC™ Reflectivity cure for a series of SiN thickness from 0 to 300nm. Of particular interest is the choke point at 70nm.

It is helpful to re-iterate, the bake window is defined at the lowest temperature [highest solubility] where isolated lines are stable with BARC undercut, and the highest temperature [lowest solubility], where dense spaces are clear, no scumming or footing. Hence dark field processes are performed with larger process window due to the higher acceptance of BARC undercut for high energy implant [and etching] applications.

4. Optimization considerations for BEOL

4.1. Dual Damascene integration.

As the CDs of devices has decreased, thus decreasing gate delays and increasing chip functionality, interconnect feature size have also been reduced, resulting in higher line resistance. More dense interconnect can result in higher line-to line capacitance. To compensate for this, IC manufacturers are moving to copper because its conductivity is 40% higher than aluminum [21]. Unfortunately, conventional aluminum processing techniques [blanket metal deposition followed by photoresist masking, followed by reactive ion etching of aluminum], are extremely difficult to replicate for Cu in traditional low-temperature RIE equipment. As an alternative, the Damascene process has been introduced. Where the insulator is deposited, the trench is first etched [using a reverse image photoresist mask] to the desired depth [or stopped with an etch-stop layer], liner and metal are deposited and excess metal is polished off utilizing CMP. The more common process incorporates the definition of via [or contact] pattern in addition to the trench patterning prior to liner and copper deposition. This process is known as Dual Damascene.

As the Damascene process is complex, there are a number of different integration possibilities. These include trench first, buried etch mask; buried etch stop; and via first. The incorporation of BARC into the most common scheme:- via first, will be discussed in detail.

4.2 Via first BARC process

The primary advantage of this scheme is the inclusion of via fill material that reduces the topography encountered when printing the trench mask. It can also provide lower cost of ownership as CVD and plasma depositions of the barrier layer, inter layer dielectric and hard mask can be applied within a single cluster. In addition to the reflection control required over the varying thickness and underlying stack of oxide, the via fill BARC also protects over-etch at the base of the via while etching the trench.

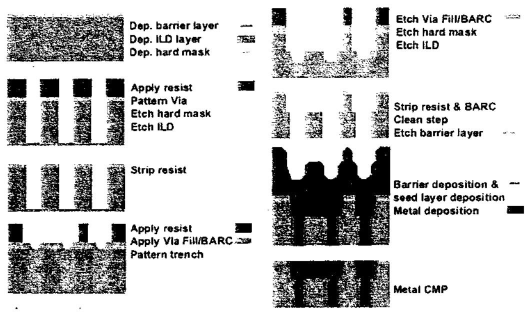

Figure 13. A schematic representation of via-first technique for Dual Damascene. The diagram shows full via-fill with organic BARC.

Initial techniques focused on partial filling of the via [due to concerns about "fencing" or "crown" formation around the via while etching the trench.] [22]. However, due to the density of vias, the remaining volume in the via is filled by the photoresist, resulting in a large bulk effect within the resist thickness variation. Therefore even with total swing curve suppression, the residual bulk effect resulted in large CD variation within the via array and a bias between dense and isolated vias. Consequently, the industry quickly moved to full fill via-first Dual Damascene processing [23].

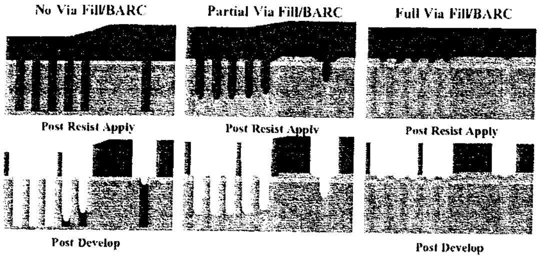

Figure 14. A schematic representation of the resist thickness variation between no via fill, partial fill with BARC and a full fill BARC process [24].

With all spin coating techniques there exists a thickness bias between filling dense areas and isolated areas [due to the mass balance] but, by modifying the molecular weight distribution of the BARC it is possible to reduce this.

When setting up the BARC process, a relatively thick BARC layer is used to ensure full filling of the vias. Further, for some users it has been desirable to "over fill" the via areas, resulting in a totally planar surface.

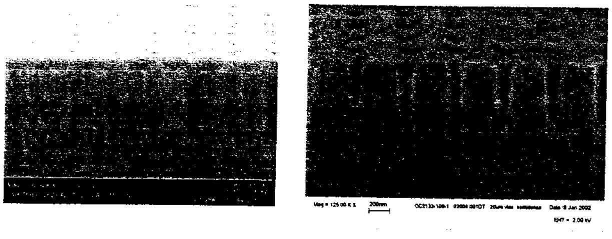

Figure 15. Examples of full fill and partial fill KrF BARC. 0.2 µm vias of 1.0 µm deep vias in oxide. 15a shows over filled vias and 15b shows partially filled vias.

It can be seen from the reflectivity curve shown in figure 16 that, provided the thickness of BARC at the center of a dense array of vias remains above 60nm, the reflectivity remains below 6%

4.3 Etch considerations for full-fill via-first integration.

Having established the photo process, etching the BARC and dielectric stack also offers new challenges. The rudiments of BARC open etch technology has already been discussed. However, for Dual Damascene integration there is a specific consideration for BEOL BARC open, namely the elimination of the crown or fence.

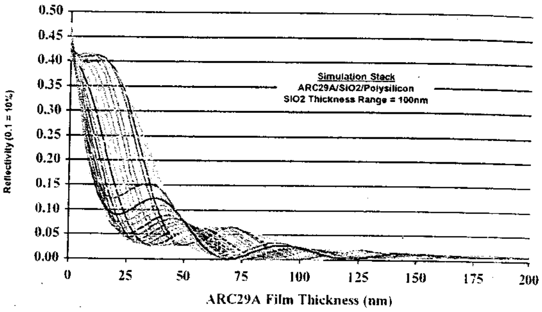

Figure 16. Tornado plot for ArF BARC ARC29A over 100 nm variation of oxide. The familiar choke point is demonstrated at 60 nm thickness of BARC.

4.3.1 BARC open and fence elimination..

In general, elimination of fencing can be achieved by judicious choice of etch gas ratio [e.g. CF_4/CH_2F_2 for BARC and CF_4 for SiO_2], to balance the degree of polymerization with that of side-wall erosion and the bulk etch rate of BARC within the via. This is to ensure high selectivity with the resist, maintain flat etch fronts and sustain side wall angles.

To simplify this process, a BARC etch-back process can be adopted. This process removes the BARC to below the trench etch stop level. Thus, when etching the trench, little organic material remains within the trench depth reducing the degree of fencing. Care is taken to ensure sufficient organic material remains in the via to protect the base of the via. In general for a low k stack with "low-k etch stop" the process will include many gas changes: BARC open and over-etch CF_4/CH_2F_2, PECVD Low-k etch, $C_4F_8/CO/N_2/Ar$, and etch stop open $CF_4/CHF_3/Ar$ [25]. This slight modification is to ensure higher concentrations of fluorine atoms. Further, the CH_2F_2 is employed as the polymerizing gas for side-wall passivation and improved selectivity.

Due to the intricacy of this process, some IC manufacturers are considering testing Cu for only one or two of the upper levels of metalization [where most power is carried], to learn the complexities of the process. Initially, conformal BARC coating is considered as the etch protection is not needed [due to high selectivity of the dielectric etch and the exposed metal at the base of the via]. However, most decide on a full fill approach from the beginning as this [once learnt] is transferable through the whole stack [22].

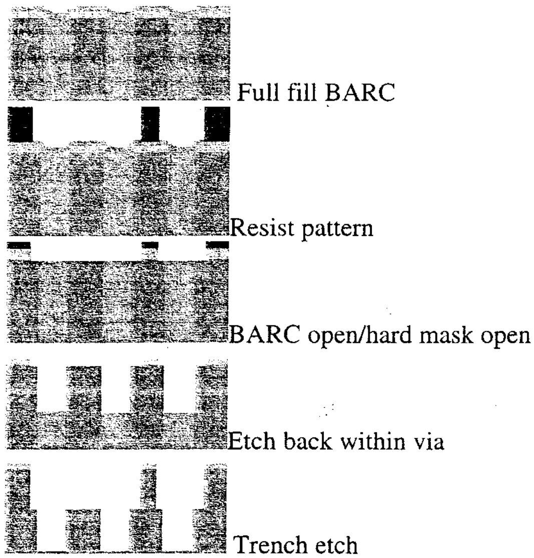

Figure 17 represents the BARC etch-back process employed to eliminate the fencing which can be possible during the trench etch [24].

5. Conclusions

We have presented the reader with a step-by-step approach to BARC process optimization and the background to three applications encountered by lithographers and etch engineers working with organic BARC. The initial work focused on optimizing the lithography settings of the exposure tool and choosing the best matched BARC and photoresist. It then dealt with optimization of the thickness for both resist and BARC to minimize the CD dispersion; at this point, the lithographers and etch engineers decide on the optimal coating performance; planarizing [for efficient lithography] or conformal [for ease of etching]. New technology for front-end processing and ion implantation was discussed where the introduction and optimization of a wet patterning BARC process was presented. Finally the BARC coating considerations for BEOL Dual Damascene integration was discussed with examples of partial fill, and full-fill technology, the latter being recommended. Finally suggestions for etch optimization were presented.

Having provided the basic theory to BARC technology [1] and the concepts to material design and how they are applied to different applications [2], the reader now has the fundamentals of BARC optimization described for three common applications.

6. Acknowledgments

Jo Mayo, Shree Deshpande, James Lamb III, and Andrew Waite-Wright are thanked for their contributions, help and useful discussions in the preparation of the article.

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