Factors that Determine the Optimum Dose for Sub-20nm Resist Systems: DUV, EUV, and e-beam Options

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ABSTRACT

As EUV and e-beam direct write (EBDW) technologies move closer to insertion into pilot production, questions regarding cost effectiveness take on increasing importance. One of the most critical questions is determining the optimum dose which balances the requirements for cost-effective throughput vs. imaging performance. To date most of the dose requirements have been dictated by the hardware side of the industry. The exposure tool manufacturers have a vested interest in specifying the fastest resists possible in order to maximize the throughput even if it comes at the expense of optimum resist performance. This is especially true for both EUV and EBDW where source power is severely limited. We will explore the cost-benefit tradeoffs which drive the equipment side of the industry, and show how these considerations lead to the current throughput and dose requirements for volume production tools. We will then show how the resulting low doses may lead to shot noise problems and a resulting penalty in resist performance. By comparison to the history of 248 nm DUV resist development we will illustrate how setting unrealistic initial targets for resist dose may lead to unacceptable tradeoffs in resist performance and subsequently long delays in the development of production worthy resists.

1. Introduction

Pre-production EUV exposure tools and prototype e-beam direct write (EBDW) tools have now been delivered to the first customers with target insertion points below 20 nm[1,2]. However, resists capable of producing usable patterns at these resolution levels remain to be proven. Meeting the simultaneous requirements of resolution, sensitivity, and line edge roughness (LER) as well as production standards for critical dimension uniformity (CDU), stability and batch-to-batch control remains a serious challenge[3,4,5]. Compounding the difficulty of this task are the extreme sensitivity requirements being driven by the tool suppliers, in large part due to low source power (a problem for both EUV and e-beam) and the overriding need to maintain high throughput. Putting the need for speed first and forcing the resist sensitivity into the role of a dependent variable must necessarily lead to serious compromises in resist chemistry and performance.

In this paper we will model the driving forces behind the throughput targets and the resulting dose requirements. We will then consider whether the sensitivity values currently demanded by the exposure tool roadmaps can be met in a usable manner. By way of comparison, we will look back at the early days of deep ultraviolet (DUV) resist development when tool limitations drove similar dose considerations and show how the resulting drive for ultra-fast resists compromised the introduction of DUV technology. We will conclude with a look ahead at future scaling considerations for viable sub-10 nm process technologies.

2. Economic Drivers: How Cost per Function Drives Throughput Requirements

The semiconductor industry has enjoyed decades of unparalleled success by following one simple metric: the cost per function must always go down over time. As embodied in the form of Moore's Law[6], the industry has become accustomed to think that resolution drives cost reduction, and that as long as resolution shrinks by 70% per node on a 2 year cycle the cost reduction requirement will automatically be satisfied. In fact this simplistic devotion to resolution ignores the role that productivity and other factors play in achieving the overall goal of reducing the cost per function. While it is beyond the scope of this paper (and the interests of a resist technology conference) to explore a complete cost benefit analysis, a simplified model is useful in understanding the drivers in lithography and hence in resist development. Fig. 1 shows a graph of leading edge exposure tool cost over time[7]. While there are fewer publicly available data points now than in the past, the exponential growth has been remarkably constant; the doubling rate has changed only slightly from every 4.3 years to every 4.1 years over the past three decades[8].

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The industry has been able to afford this rate of cost increase because the tools themselves have become more productive at an even faster rate, resulting in higher value of ownership despite the higher cost of ownership. To study the ratio of productivity vs. cost we use the simple concept of a resolution element, or pixel, as a proxy for the functional elements printed; we define the pixel as a square with a side equal to the minimum resolution of the tool. As seen in Fig. 2, exposure tool productivity expressed in megapixels/hour has grown faster than the tool cost; the rate of productivity doubling is roughly once every 3 years. The resulting cost per megapixel has therefore declined steadily over time (Fig. 3). This increase in productivity has been led by shrinking resolution coupled with higher throughput, larger wafer sizes and more efficient production control. The role of wafer size in particular is clear in the figure, where major size changes appear discontinuous gaps. In reality the wafer size transition and resulting cost benefit tends to spread out over several years.

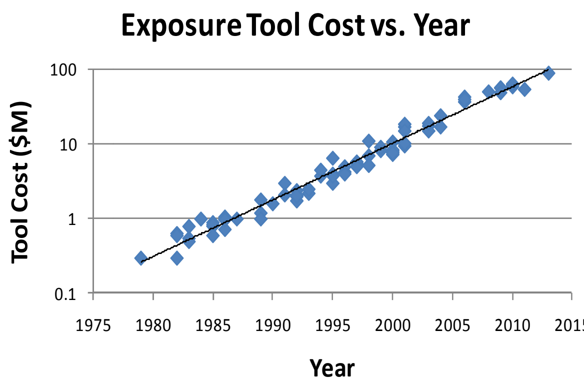
Over the past decade, however, many of these improvements have reached plateaus which will be increasingly difficult to overcome. Wafer size has stalled at 300 mm and throughput improvements, while impressive, have slowed. Exposure field size has not increased in 15 years, removing one more knob which might help throughput. The introduction of multiple stage exposure tools gave a boost to raw throughput values, but going much faster would require extensive redesign not only of the scanners, but also the track systems, which themselves have grown in size and cost to keep up with the exposure tools. Utilization rates have held roughly constant as more automated self-monitoring and correction systems have helped offset the increasing complexity of the tools, and advanced process control (APC) systems in fabs have evolved to minimize lost time due to load balancing, process monitoring and diagnostics.

Looking ahead, the proposed transition to 450 mm wafers, while clearly beneficial in the long run, is subject to ongoing financial uncertainty and faces years of additional development. It is highly unlikely that 450 mm EUV or EBDW tools will be available for many years. More critically, since these tools are essentially limited by available source power, larger wafers would necessarily take longer to fully expose, keeping the area exposed per unit time constant. This leaves resolution as the most effective variable left to drive productivity, and it must not come at the expense of throughput. A higher resolution, lower throughput tool will result in a higher cost per function, breaking the decades long model for the entire industry.

The simple model described here can be expanded to accommodate a large number of other cost-benefit factors such as tool utilization, number of exposures required, mask cost and fab footprint. We will not go into these factors in detail, but we should note a few key implications. The throughput values used to compute pixel rates in Figs. 2 and 3 represent actual production rates, which are significantly less than he quoted maximum tool specifications. The actual de-rating value is highly dependent on how the tools are used and maintained, the resist process, and the product mix (memory, logic, or foundry). It is clear, however, that the utilization rate of any vacuum based tool can only be worse than a non-vacuum system since any significant repair procedure will require breaking vacuum followed by a pump down and requalification cycle. This limitation will clearly drive the need for maximum throughput when the tool is running.

It should also be noted that this model is for a single exposure only. As chips have become more complex, the number of critical layers has grown substantially. A complete model for the total fab cost per function is beyond the scope of this paper. However, it should be clear that a process requiring multiple exposures for a single critical layer would suffer a significant productivity loss compared to a single exposure. This underscores one of the primary economic drivers for EUV. If a layer can be exposed with only a single pass, even with a more expensive, lower throughput tool, it may still be more cost effective than a multiple exposure (and/or multiple deposit and etch) process on a lower cost, higher throughput tool.

The clear message from this analysis is that any new tool – EUV, EBDW, or any other alternative – must run at a sufficiently high throughput to keep the cost per function on a downward trend. For tools with low power sources, this drives a requirement for very low dose resists. Fig. 4 shows our model output comparing the tool cost per million pixels printed for a 193 nm immersion tool vs. the potential cost for EUV and EBDW systems at various throughputs either achieved to date or projected. This chart shows only the pure tool cost, not including masks or clean room space, and making the optimistic assumption that utilization rates for these systems will eventually reach the same levels as more mature 193 nm immersion tools. It is clear that EUV will not produce achieve lower cost per function unless throughput exceeds 100 WPH. Given the limited source power available to date, this drives the need for very fast resists; published EUV roadmaps[1] call for 10-15 mJ/cm^2. Similarly, EBDW may be viable at lower throughput rates (especially when one



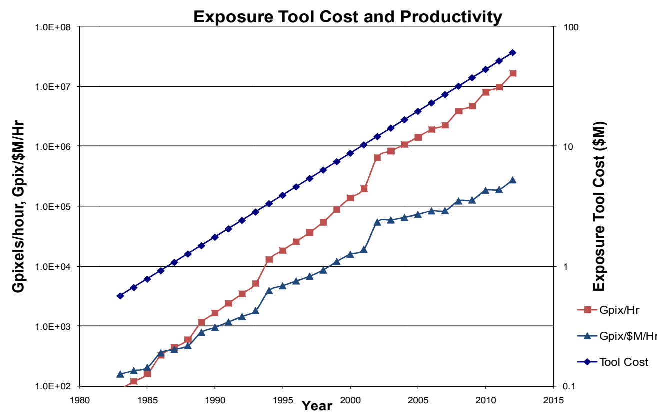
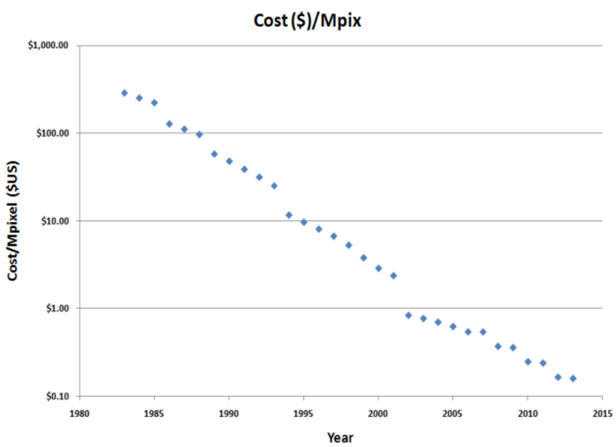


Figure 1: Exposure tool cost vs. year of introduction. Data from multiple suppliers and users. Exponential fit shows cost doubling every 4.2$\pm$0.2 years.

Figure 2: Exposure tool cost and productivity (measured in Gigapixels/hour and Gpix/$M/hour) over time. Rate of productivity increase outpaces growth in tool cost.



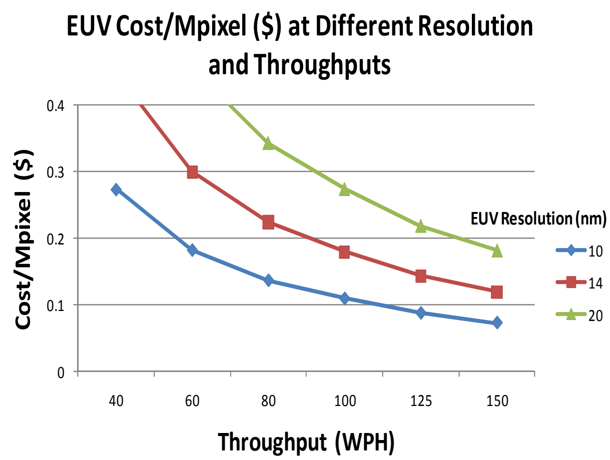


Figure 3: Cost per megapixel over time. Discontinuous jumps indicate wafer size changes. Cost declines over time as productivity outpaces rate of tool cost growth.

Figure 4: Projected EUV cost/pixel at different resolutions and throughputs. Tool cost is assumed to continue rising at the historical rate. There are no corrections for tool availability, double patterning, mask costs or impact to the total fab due to slow exposure tools.

eliminates mask cost), but the required levels are still orders of magnitude higher than existing R&D tools have achieved. Published roadmaps[9] for EBDW likewise call for very sensitive resists, on the order of 30 $\mu C/cm^2$. In the following sections we will explore whether such targets are physically viable and consider the tradeoffs that occur when tool limitations have driven resist development in the past.

3. Early DUV Resists: Lessons We Should Learn

This is by no means the first time a promising exposure technology has been driven to perform at low dose due to limitations in available source power. The early DUV tools, based on Hg arc lamps or very early excimer lasers, operated under similar constraints[10]. It is worth a brief review of these early 248 nm resists to see what lessons we can learn. Because of the very low flux of DUV photons in the first Perkin Elmer Micrascan (and even the last Micralign) tools, dose targets were in the 1-5 mJ/cm^2 range, orders of magnitude less than the existing g- and i-line resists. Excimer laser based steppers like the GCA AWIS had higher power at the wafer plane, but the lasers needed frequent overhauls as a function of shot count, so similar fast resists were desired to maximize throughput and minimize shot count[11]. This led to the invention of acid catalyzed resists, which are now the standard for high performance production resists, but at the time they were both novel and incredibly unstable. Heroic efforts by Ito, Willson, Frechet and colleagues resulted in formulations with sensitivities below 1 mJ/cm^2 but with virtually no stability for processing. tBOC styrene resists with superacid onium salt catalysts were used as negative tone resists in the 1 mJ/cm^2 range and positive tone versions ran at roughly 5 mJ/cm^2. All of these systems suffered from instability, excessive sensitivity to poisoning by airborne molecules[12] (amines), and the use of metal salts. Non-metal onium salts were developed by IBM in Fishkill; roughly two times slower than the earlier versions, they were considered suitable for use in the earliest tools.

By 1991 the next generation excimer lasers with power output of around 4 watts were available with greatly enhanced component lifetimes, producing on the order of 100 mW/cm^2 at the wafer plane[13]. Not only could these new tools operate at much higher doses, they actually could not use the faster resists; the laser pulse rates were too slow (200-400 Hz) to accurately control doses < 10 mJ/cm^2 to the required 1% level. The first truly production worthy DUV resist, APEX-E, was sampled by IBM to other users in 1993. Operating in the 10-40 mJ/cm^2 range depending on PEB temperature, APEX-E was still subject to poisoning by environmental contaminants, but at a controllable level. This resist and its successors, notably IBM ESCAP, took advantage of the higher dose to add base quenchers, enabling higher contrast and greater resistance to contamination, and the high dose/lower PEB combinations led to more stable processes[14] (Fig 5).

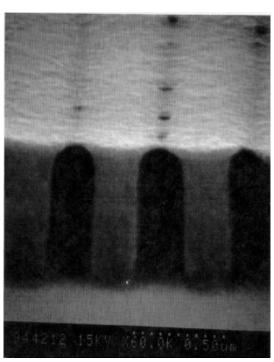


Figure 5a: Early DUV resist showing extreme T-topping due to environmental contamination.

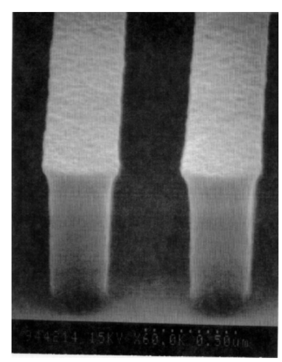


Figure 5b: Same resist and exposure to airborne contamination, reduced T-topping by use of lower PEB temperature and higher dose. Raising the dose further eliminated all T-tops.

Fifteen years after the initial attempts at ultra-sensitive resists, systems operating at 20-50 times higher doses finally made DUV viable for production. Research into a huge number of dead end chemical formulations pursued in the interim filled many volumes of conference proceedings but never resulted in production worthy resists. If a more appropriate dose target had been selected at the outset, it is possible that many years of effort could have been saved and DUV could have been ready several nodes ahead of its eventual adoption. Of course a counter argument could be made that the delay in adopting DUV extended the life of i-line as a more cost effective choice, and that setting the initial target so low forced the critical invention of chemically amplified resists, the workhorse of all current leading edge processes. In that sense, the unrealistic initial target paid a handsome if unintentional dividend.

4. EUV Resist: Implications of Shot Noise on Dose

We will now investigate the relationship between dose and shot noise for EUV. The exposure process actually consists of a series of stochastic processes: the exposure itself, which consists of a finite number of photons per unit volume; the probability that any given photon will be absorbed and generate a photoelectron to initiate a cascade or lower energy electrons which in turn have a probability of being captured by a PAG molecule to generate photoacids; the diffusion and catalytic amplification of the photoacid molecules; and the development process. Numerous papers have studied different aspects of the stochastic chain in detail[15,16,17], and recent models have successfully linked a number of these discrete steps[18,19] to provide valuable insight into the total level of noise and its impact on LER and CDU. These complex models require a wide range of physical and chemical inputs and are well beyond the scope of this paper. For our purposes, we will focus as much as possible on the first step in the chain, namely, the shot noise inherent in low dose exposures with high energy photons.

Due to the limited power of 13.5 nm sources and the low transmission of the reflective optical chain, EUV power at the wafer plane will be seriously limited even assuming that the sources will eventually meet the roadmap targets of 100-500 watts. In order to specify a cost effective throughput target of 100 or more wafers per hour, the target dose commonly mentioned is 10-15 mJ/cm^2. Since the energy per EUV photon is over 14 times greater than for 193 nm, this low dose results in photon numbers where shot noise can be significant.

In order to compute the shot noise, we need to determine an effective area over which to integrate the photon flux. The area of interest is actually much smaller than the effective pixel size (minimum resolution squared). Even when exposing a fairly large area of many tens of nanometers, the large number of photons striking the middle of the structure does not play any role in the development of the resist profile at the edge of the pattern. A better approximation of the region of interest is to look only at those photons which will play a role in delineating the developed resist edge, a region defined by the resist blur[20,21]. Since edge roughness is a function of the noise times the image log slope[22] (ILS), large areas will have less LER than minimum size features, but the improvement will scale with ILS, not the feature size squared. The blur region is strongly coupled to resolution and is generally on the order of one-half of the minimum feature[23,24]. We will refer to this as the interaction range as the ambit. Increasing acid diffusion in the resist and hence the blur will increase the number of photons per unit area at the resist edge, reducing LER, but at the cost of resolution.

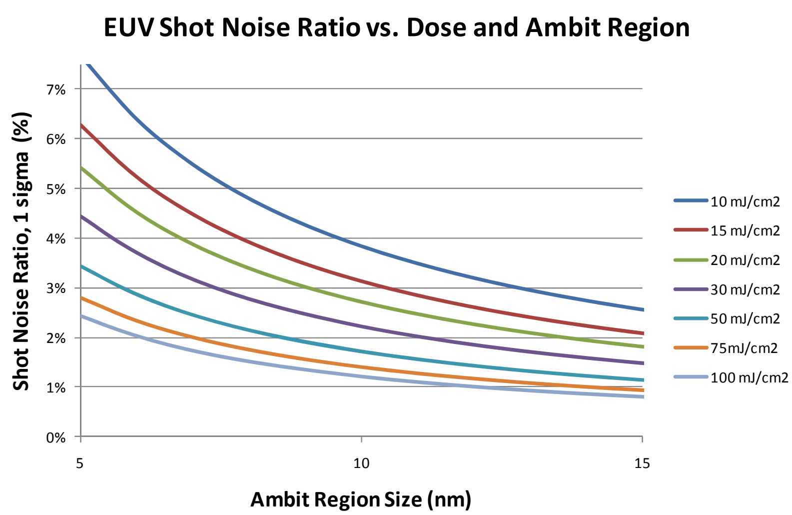


Figure 6: Shot noise ratio for 13.5 nm photons as a function of dose and effective interaction region within the resist (ambit) which should typically be on the order of one half to one third of the minimum CD.

Fig. 6 shows the shot noise ratio computed for different doses and ambits. Shot noise is defined as the square root of the variance over the mean and follows Poisson statistics. For a Poisson distribution the variance equals the mean, so the noise ratio is just (√N)/N, where N is the number of photons in the ambit. Since the number of photons goes as the square of the ambit, the ratio goes as 1/(ambit); the number of photons is linear with dose, so the ratio goes as 1(√dose). Note that this is a one sigma value. To estimate the full width of the noise distribution we should really consider 3 sigma as the parameter of interest since the Poisson distribution becomes indistinguishable from a Gaussian when N is greater than a few hundred.

For a 10 nm ambit and a dose of 15 mJ/cm^2 each 100 nm square unit area would receive a nominal exposure of just over 1,000 photons; 3*noise ratio is over 9%, rendering 10% total CD control problematic. To keep 3*noise ratio below 5% would require a dose of at least 50 mJ/cm^2. As the need for better resolution drives the blur down to the 5 nm level, 3*noise ratio of even 7.5% would require a dose of 100 mJ/cm^2. This calculation simply counts photons. In a real resist system, not all of the photons are absorbed in reactions which generate useful photoelectrons, making the shot noise in the resist even worse.

Photon noise does not necessarily translate directly into line edge roughness. Diffusion and other averaging processes may help reduce LER, but at the cost of longer range CD uniformity, MEEF or exposure latitude[25,26]. For example, if the development process smoothed the line edges, the LER would improve but the location of the edge would vary. The relationship between CD uncertainty and LER can be summarized as[27]

$$\sigma_{CD} \sim \log(L_c) \times \sigma_{LER} \quad (1)$$

Filtering can reduce σ_{LER} but it also increases the correlation length L_c and therefore the longer range CD uniformity error. As with any system with a noisy input, filtering is possible but at the expense of fidelity.

It is clearly advantageous to have higher quantum efficiency and PAG loading to generate more photoacids and increase the chances of a single photon setting off a lithographically useful reaction, but amplification can not undo the initial photon noise; it can only keep it from getting worse in the ensuing stochastic processes. The only way to smooth a noisy input signal through amplification is to drive the system to a saturation limit, but again, while this would produce smoother edges, the location of the edge would become more uncertain.

The current champion resists (barring major new announcements at this conference) have roughly 20 nm resolution and 3 nm LER at doses in the range of 10-20 mJ/cm^2. These LER values are at least 50% worse than even the basic shot noise model would suggest. Clearly current resists are not shot noise limited; other stochastic processes, including the impact of out of band radiation, must also play a major role[4]. As these other variations are reduced by increasing resist absorption, higher PAG loading and other means, the photon shot noise limit will remain. Other, more mathematically rigorous studies have gone into far greater detail of the exact impact of shot noise on LER[19,20]; to date there has been no definitive conclusion on the ultimate limit of LER vs. dose and the tradeoff between LER, CDU, exposure latitude and MEEF through modifications of the resist chemistry. The general scaling of photons vs. blur suggest that the limit will not be achieved without a significant increase in resist dose.

5. e-beam Resist: Implications of Shot Noise on Dose

The same considerations discussed for EUV apply equally to e-beam, with the added complication that in e-beam exposure there are additional stochastic processes related to secondary and backscattered electrons and electron penetration depth which are all dependent on the voltage and substrate material[28,21]. There is also an added blur due to Coulomb repulsion in the beam which is system design dependent. The shot noise due to the number of electrons per unit area is therefore just the first in a chain of stochastic events which will all contribute to total CD variation and LER.

The cost considerations for EBDW tools are very different from EUV. Currently the best tools that are capable of writing a full wafer take hours per wafer, and prototypes announced for testing in 2012 are still at the 1 WPH level. EBDW may not need to achieve 100 WPH to serve in several critical niche areas[29], although that is the ultimate goal of several key technology champions[30]. As with EUV, the proposed specifications to meet the desired throughput levels tend to be quite low, in the range of 30 μC/cm^2. Using these values, we plot the signal-to-noise ratio in Fig. 7. Note that the definition of ambit here is the same as for EUV; it is the effective area over which electrons can interact with the resist to define the edge of the feature. This is not to be confused with the beam spot size, which may be larger. With this definition, and staying with the assumption that the resist blur should be roughly one half the minimum feature size, we can see that for 20 nm patterns (10 nm blur) there are only 312 electrons in the ambit area even at 50 µC/cm^2 ; the resulting 3*noise ratio is over 17%. The dose would have to increase to 150 µC/cm^2 to reach 1,000 electrons per region and a 3*noise ratio of 10%.

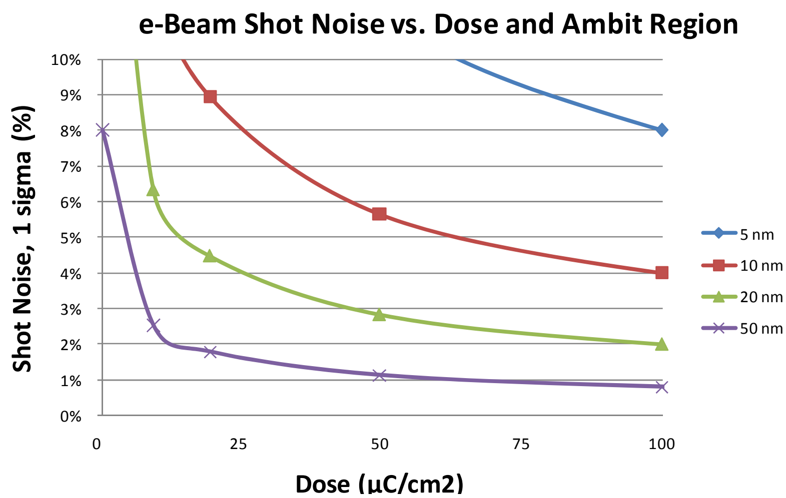


Figure 7: Shot noise ratio for EBDW as a function of dose and effective interaction region within the resist (ambit).

These numbers are in rough agreement with earlier, more detailed modeling by Kruit et al who studied 45 nm lines with an effective resist interaction regime of 25 nm[21]. Their conclusion was that 30 µC/cm^2 was the dose required for acceptable LER and CDU, corresponding to 1170 electrons/unit area. This is consistent with our estimate of a minimum required dose of 1,000 electrons in the ambit region. Since we are now looking at features in the 20 nm range, the resist interaction region will be 4 times smaller and the required dose 4 times larger. Even with improvements in other resist parameters, the minimum dose required is clearly several times larger than currently used to print larger demonstration features.

6. 193 nm: Implications of Shot Noise on Dose

193 nm photons carry only 6.4 eV of energy as compared to > 92 eV for EUV. As noted earlier, this means that at a given dose, there will be over 14 times more photons per exposure for 193 nm than for EUV. Nonetheless, this does not mean we can arbitrarily lower 193 nm doses. With a 10 nm effective ambit, 3*noise ratio is 2.2% for a dose of 20 mJ/cm^2, a value that is typical of the fastest production resists in use for the current leading edge processes. Even if faster 193 nm tools require doses as low as 10 mJ/cm^2 that would only raise the value to 3% which could be acceptable depending on how all of the other stochastic processes scale. It would seem that 193 nm will run out of resolution before photon shot noise becomes a limiting factor.

7. Conclusions

For both EUV and EBDW, the doses currently being targeted based on throughput and cost considerations appear to be too low to achieve acceptable LER and overall CD performance. The shot noise due the low number of exposing quanta, either EUV photons or electrons, is not yet the limiting factor in resist performance, but it sets a clear floor.

We have seen in our discussion of early DUV resists how unrealistic dose targets imposed by source limitations led to extensive delays in achieving production quality materials. At that time, delaying DUV simply meant extending i-line lithography with aggressive OPC, phase shifting, and tighter process control, all of which were enormously beneficial to the industry. In the end, when the industry shifted its sights to more reasonable dose targets, our colleagues in the resist world were able to implement new ideas that enabled the next 20 years of progress in lithography. This improvement in "wetware" was absolutely as critical as the improvements in hardware[31]. As we look ahead at the sub-20 nm nodes, it does not appear that we have the luxury of chasing the wrong target for too much longer. If there is a path to a better resist that breaks away from current formulations but at the cost of higher dose, history and physics suggest that we should not reject these ideas out of hand simply because they are too slow. It is especially important to bear this is mind as some researchers are now suggesting that existing CAR platforms may not be extendible below 16 nm. If new platforms are required, we must be diligent not to prematurely discard any promising candidates simply because they fail to meet an unrealistic dose target.

The other lesson we have learned time and again in this industry is that we always need to aim ahead of the short term target to develop successful processes. EUV has been mentioned as a candidate wavelength since the 130 nm node. Today people speak about 20 nm as the target, but realistically the technology may not be ready for volume insertion even then. The same applies for EBDW. Resists in development today should ideally be targeting the 14 nm or even 10 nm nodes to insure that they not just ready for initial insertion but that they are also extendible to future nodes. Since shot noise only gets worse as we try to print smaller features, resist development should look at the real dose requirements of the next node, not the past nodes. Throughout the history of microlithography, advances in resist chemistry have been as important as advances in exposure tool technology[32]. In order to maintain this impressive history of technology enablement we must be sure we are aiming at the right targets ahead of us, not behind us.

8. Acknowledgements

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