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Prospects for Optical-, EB-, and X-Ray Lithography for Giga-Bit Memory: Advantages and Disadvantages

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1. Introduction

Progress of DRAMs has always been driven by improvement in optical lithography. This paper discusses optical-, electron beam (EB)-, and X-ray lithography methods in terms of production of future DRAMs in the sub-0.2 μm regime.

DRAMs consist of a repetitive memory-cell pattern and logic circuitry. While a smaller cell size has been intensively pursued for strong economic reasons, higher performance in the logic part of the chip is also important, especially in merged DRAM-logic (MDL). Lithography has to meet these different requirements at the same time. Several changes now being introduced for next-generation DRAMs are expected to reduce difficulties in lithography. First, introduction of chemical-mechanical polishing reduces the large topography due to a stacked capacitor structure, and this relaxes the severe requirement for the depth of focus in optical lithography. Second, introduction of a self-alignment scheme, like self-aligned contact relaxes the requirement for alignment accuracy. These non-lithographic approaches are also very effective for shrinking the cell area.

2. Fundamental limitation

The fundamental resolution capabilities of each lithography method are compared in Fig. 1 [1]. Here, line-width variation caused by 5% dose change is plotted as a function of pattern feature size. These figures clarify the minimum necessary specifications for each method.

By combining an ArF excimer laser (λ=193 nm) with various resolution enhancing methods, such as a phase-shifting mask (PSM), optical lithography can produce geometry as small as 0.1-μm (this depends on the type of pattern features). The possibility of utilizing wavelengths shorter than 193 nm is questionable because of difficulties both in design and in materials for optical systems. Figure 1 also shows continuous improvement in exposure systems is necessary also in EB and X-ray methods.

3. Pattern design restriction

In optical lithography, the resolution capability strongly depends on the types of pattern feature and the methods of resolution enhancement. In general, optical lithography is good at printing simple 1-dimensional (1D) features. Fortunately, most of the finest geometry in real devices belong to such patterns, especially in DRAMs. Optical lithography should take full advantage of this; that is, building circuitry from simple 1D patterns is the key. An exposure scheme should be chosen so as to minimize the cell area, where a small number of highly sophisticated patterns are required, taking full account of the optical effect (i.e. optical proximity effect correction: OPC). This procedure requires establishing an environment where layout designers and lithographers can cooperate. To achieve this, better understanding of optics and process is indispensable. For a memory cell, the achievable finest pitch is about 0.12 (0.16) μm using an alternating PSM and a negative-tone resists with an ArF (KrF) excimer laser, while the narrowest gate line in the logic circuit is also about 0.12 (0.16) μm using a phase-edge PSM and a positive-tone resist (though this requires double exposures). Achieving the finest resolution for both these parts of the chip is a challenge, and several options are available as a compromise, i.e., attenuated PSM for the logic part of the chip.

Other lithography methods have less pattern restriction than optical lithography. In X-ray lithography to improve resolution down to 0.1 μm, however, the mask-wafer gap has to be decreased. This makes OPC necessary also in X-ray lithography, and this requires mask CD control as accurate as a few nanometers.

4. Throughput vs. Resolution

Throughput is very important in DRAM manufacturing and is the most critical problem in EB lithography. To increase the throughput of EB lithography, improving resist sensitivity, increasing beam current, and introducing a new exposure scheme (such as the cell projection (CP) method) are key issues. Although the CP is suitable for repetitive DRAM patterns, several EB machines will be needed to replace one optical stepper even with optimistically assuming resist sensitivity of 1 $\mu C/cm^2$.

Fundamental factors to limit practical resolution of EB lithography includes the beam blur and diffusion in resist films of chemical species (acid) generated by irradiated energy. The beam blur σb is limited by the Coulomb effect and increases proportionally to the beam current J ($\sigma b \propto J$). The acid diffusion length σd in the chemically amplified resists increases when using heavy catalytic reaction conditions for attaining higher resist sensitivity (i.e. $\sigma d \propto S^{-n}$, S: the dose required for exposing resist:). Because the time required for exposing the resist is given by J/S, there is a trade-off between resolution and throughput ($\sigma b \bullet \sigma d^{-n} \propto J/S$).

All the diffusion coefficients reported for deep-UV nresist so far are in the range between 10^{-5} and 10^{-4} $\mu m^2/s$. These values are sufficient for achieving 0.15-0.3 μm pattern sizes but will cause a serious problem below 0.15 μm. This will be also serious in optical and X-ray lithography methods. To achieve practical throughput in X-ray lithography, less than 100 mJ/cm^2 sensitivity is required. In contrast, in an ArF excimer laser, sensitivity less than 5 mJ/cm^2 is required to avoid damage in materials used in the optics. These sensitivities are almost equivalent to the requirement in EB lithography (1 $\mu C/cm^2$) in terms of basic resist chemistry (quantum efficiency); thus, we will face the same order of diffusion problem. A new mechanism such as the non-Fickian diffusion may be useful for overcoming this problem.

5. Mask

Mask technology is becoming increasingly important in obtaining required accuracy both in CD and in registration. Optical- and EB- lithography have a great advantage over X-ray lithography because they can use magnified masks. Because mask error is regarded as an off-set error, it should be directly added to other errors, making its contribution more important.

Optical masks for 0.18-μm generation on masks require CD accuracy of 20 nm and pattern placement accuracy of 30 nm. The requirement for an X-ray mask should be one forth of this specification. To achieve such accuracy, a high-acceleration-voltage mask writer is the key. Other important factors includes mask inspection and repair, defect-free PSMs, and OPC.

6. Conclusions

The sub-0.15 μm regime is a challenge for every lithography methods. Optical lithography may be able to meet requirements for accuracy and throughput but only for the limited types of pattern features, forcing severe constraints on the device design. In EB lithography, trade-off between throughput and resolution is still a big issue. In X-ray lithography, development of tools for writing, inspecting and repairing masks on the order of a few nanometers is the key.

References

1) H. Fukuda and S. Okazaki, 1995 Symp. On VLSI Technol. Digest of papers (1995) 77.

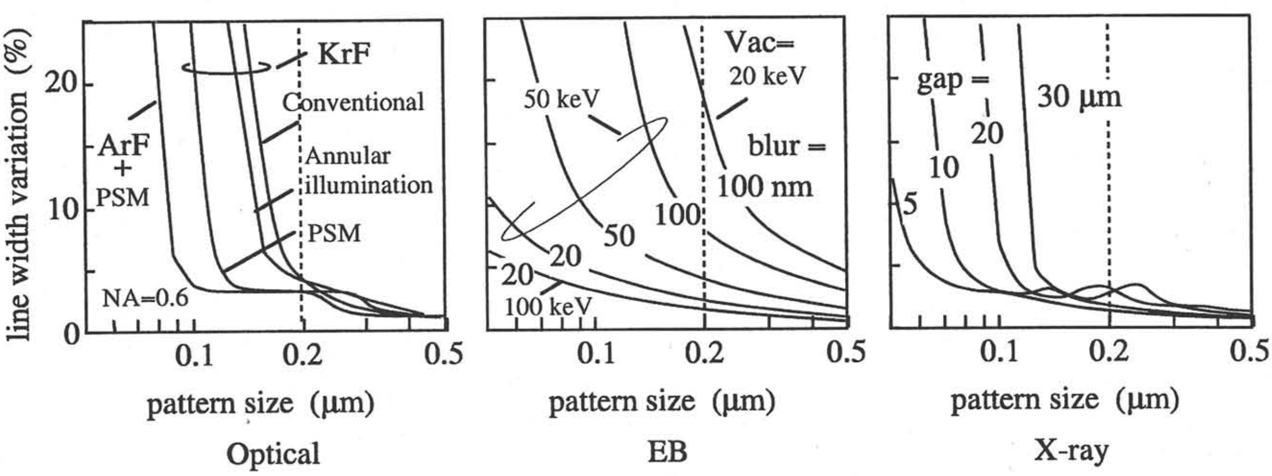

Fig. 1 line with variation caused by 5% dose change as a function of pattern size.