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The ending of optical lithography and the prospects of its successors

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Abstract

This presentation starts from recounting the history of optical lithography since its >2 μm days until the sub-100 nm era. To increase resolution and keep depth of focus in check, the wavelength has been shortened from 436, to 365, 248, and 193 nm, numerical aperture has increased from 0.15 to 0.93, the universal resolution indicator k_1, reduced from 0.8 to 0.3. There seems to be little room to extend optical lithography. Fortunately, water immersion of 193 nm light paved the way to 1.35 NA. Recent full-chip results from a 0.85 NA, 193 nm immersion scanner and remaining issues with immersion lithography are shown. From this point on, optical lithography is starting its ending. The techniques to prolong its ending, such as high-index immersion fluid and lens material, polarized illumination, mask solid immersion, double exposures, and pitch splitting are discussed. Potential successors to optical lithography include EUV lithography, high-voltage and low-voltage e-beam direct write systems. Their pros and cons and financial impacts are given.

Keywords: Microlithography; Optical lithography; Immersion lithography; EUV lithography; E-beam lithography; Direct write lithography

1. Introduction

Optical lithography has been the workhorse of semiconductor manufacturing ever since its inception. The demise of optical lithography has often been predicted but failed to materialize [1]. For example, 1 μm resolution was considered a formidable barrier. As a result, e-beam direct-write systems were developed [2], poised to take over optical lithography. X-ray proximity printing using wavelength reduced by more than 2 orders of magnitude has been perennially trying to succeed optical lithography starting at 1 μm but the attempt failed at 0.25 μm. This author predicted that optical lithography would go as far as 0.13 μm with the wavelength reduced to 193 nm, the lens numerical aperture (NA) increased to 0.65, and resolution enhancement techniques that reduces the universal resolution indicator k_1 to 0.35. However, optical lithography marched on, aided by chemical mechanical polishing that flattens the topography to reduce the depth of focus (DOF) requirement and by further increase of NA. The evolution of projection optical lithography is seen in Fig. 1. It started from the 0.15 NA 436 nm g-line lens featuring resolution over 2 μm using a k_1 factor of 0.8 through raising NA until the lens became too expensive to build at that time, reducing wavelength to reposition the NA for the next round of increase, and lowering k_1 whenever the pace of NA and wavelength changes are behind the circuit shrinking roadmap. This trend continued through 365, 248, and 193 nm and was continuing into 157 and 13.4 nm. Note that the half-pitch resolution quickly became subwavelength as early as 365 nm wavelength at 0.55 NA and 0.5 k_1. Opportunity for larger-than-wavelength imaging will reappear only at the 13.4 nm wavelength.

Enormous problems were encountered for optical lithography to march beyond 193 nm. CaF_2 the sole lens material for 157 nm lithography has the problem of attaining the required quality for 157 nm imaging at sufficient quantity and affordable price. The photoresists have too much absorption, let alone satisfying the other requirements, such as etch resistance, sensitivity, line edge roughness, post-exposure bake sensitivity, and cost. The Achilles'

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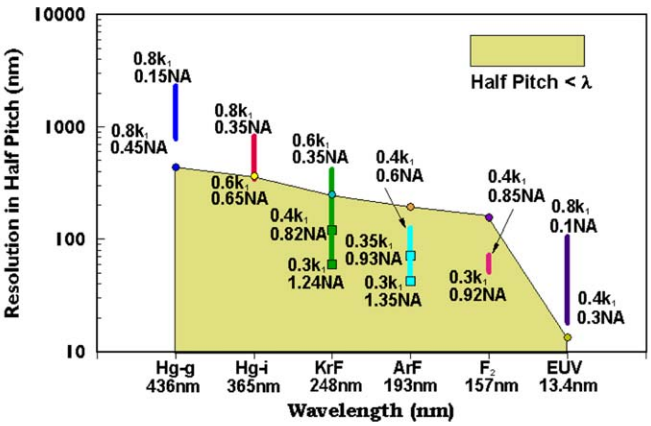

Fig. 1. Evolution of projection optical lithography from 436 nm, 0.15 NA, 0.8 k_1 to 193 nm immersion.

heel of 157 nm lithography was lack of soft pellicle for the mask. Thin-film-type mask pellicles suffer from turning opaque after irradiated with only a few 157 nm pulses. Thicker hard pellicles have to be treated as an optical element in the imaging train, requiring much higher optical quality and mounting consistency, resulting in higher cost for the former and technical difficulties for the latter.

Reducing the wavelength by more than an order of magnitude to 13.4 nm opens up a new potential to scale back the NA and k_1 for a long march to handle many more nodes. It was aimed at taking over optical lithography at 100 nm half pitch but many problems delayed its introduction.

Recently, the introduction of immersion lithography further reduces the effective wavelength of 193 nm systems to 134 nm. Using $k_1 = 0.3$ and $\mathrm{NA} = 1.35$ with water immersion at 193 nm wavelength, manufacturing of semiconductors with 45 nm half-pitch has been predicted [3].

This paper reports the progress in 193 nm immersion lithography and the problems it is encountering, followed with methods to extend 193 nm immersion lithography to its ultimate potential. The 32 nm half pitch may be a good entry point for other types of lithography. We will compare these technologies in terms of technical challenges and cost.

2. 193 nm immersion lithography

2.1. Status of 193 nm water-immersion lithography

193 nm water-immersion has been applied to logic devices and circuits to explore its potential and shake out its problems. Fig. 2 shows polysilicon images of 90 nm-node SRAM overlaid on the active layer [4]. The former was exposed on a 0.75 NA 193 nm immersion scanner and the latter, on an equivalent dry system. It demonstrated full-field imaging, a usable resist system, acceptable overlay, and large DOF. Turning to a 0.85 NA 193 nm immersion scanner, 55 nm node SRAM chips were delineated. Fig. 3 shows the metal layer image of this chip at different field locations. Fig. 4 compares the number of good dies to bad ones in a dry-immersion split at the contact layer [5]. The ratio is 72:70 vs. 62:80 despite immersion-induced defects. The number of immersion good dies would have been 25 more, attaining 97:45, if a non-photo mis-operation were discounted.

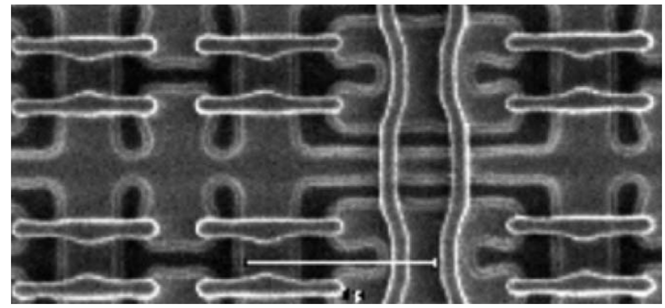

Fig. 2. Immersion chip using 90 nm-node SRAM. The poly layer overlays on the active layer. The former was exposed with a 0.75 NA 193 nm immersion scanner.

However, immersion lithography is not completely manufacture-worthy. Its wafer throughput is still slightly lower than the dry counter part. Overlay performance, though acceptable, is also slightly worse than that of the dry tools. Perhaps, the most imminent challenge is to reduce the defect level to a single digit as dry lithography. Using a state-of-the-art inspection tool, in carefully control exposures, the number of defects is found to be in double digits.

Fig. 5 shows three major defect types from immersion exposure, namely water stain, bubbles, and particles. Water stains are due to residual wetting of the resist surface after the immersion head passes through. It can be controlled by preventing residual wetting, by material treatment, and/or

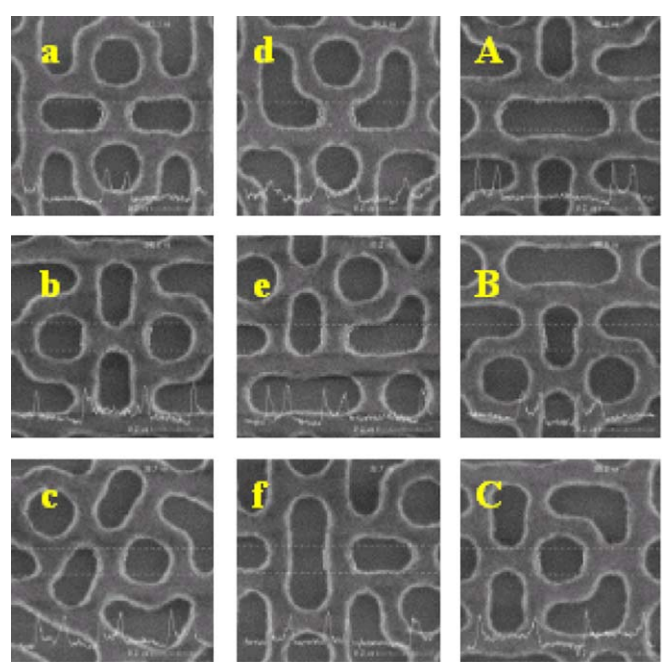

Fig. 3. 0.4 μm^2 55 nm-node SRAM metal layer exposed with a 0.85 NA 193 nm immersion scanner.