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RESOLUTION ENHANCEMENT TECHNIQUES IN OPTICAL MICROLITHOGRAPHY BASED ON MULTIPLE IMAGING

Ph.D. Thesis Synopsis

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Szeged
1999

1. Preliminaries and Goals

In December 1947 three researchers - William Shockley, John Bardeen, and Walter Brattain demonstrated a device called transistor that changed the way humankind work and play in the second half of the twentieth century. After the early paper-clip-size transistors, miniaturizing and integration became the main streamline for inserting more and more transistors into the same place.

Today's advanced computer chips contain millions of transistors on a surface not even half the size of a postage stamp. In 1965, seven years after the integrated circuit (IC) was invented, Gordon Moore observed that the number of transistors that semiconductor makers could put on a chip was doubling every year. In 1975 the pace slowed to a doubling of transistors every 18 months. The National Technology Roadmap for Semiconductors developed by the Semiconductor Industry Association extrapolates current trends to the year 2010, when 0.07 μm minimum feature size enable 64Gb DRAM chip production. The question is what technology can provide such resolution?

Integrated circuits or chips are probably the most complex of man-made products. These three-dimensional structures are the result of a multi-step process. Each step, from design to packaging must be executed perfectly if the chip is to work. Optical lithography is a crucially important and critical step in the present IC manufacturing process. During this process the patterns on the mask are imaged into a photo-resist by means of a computer controlled machine called stepper. The system and process parameters determine the obtainable critical feature size (*CD*). Reduction of the illumination wavelength and/or the use of higher numerical

aperture projection lens are two traditional methods to enhance the resolution of the optical system. However, these techniques significantly decrease the depth of focus (*DOF*) of the image. This issue can be addressed by means of new methods and technological processes that could enhance both the spatial resolution and the depth of focus. This thesis focuses on a comparative study of five resolution enhancement methods. The first technique to be discussed is an advanced phase shifting technique called **interferometric phase shifting combined with off-axis illumination**. This technique does not require any phase shifting layers on the mask, and therefore it is free from any undesirable effects caused by the phase shifting layer. The second **(annular illumination)** and third (**coated objective**) techniques are historically used to enhance optical resolution in various areas of science from microscopy to astronomy. Here they are studied and evaluated from the lithography point of view. The fourth technique **(image duplication by means of a birefringent plate)** utilizes the fact that a birefringent plane-parallel plate inserted behind the projection lens shifts the foci generated by the ordinary and extraordinary rays to different extents. The final image is
the superposition of these images. The fifth technique **(coherent multiple imaging by means of a Fabry-Perot etalon)** uses a Fabry-Perot etalon between the mask and the projection lens. The etalon generates multiple virtual 1x images of the mask along the optical axis, and the projection lens creates their superimposed image. The resolution and depth of focus could be enhanced simultaneously using appropriate initial system parameters.

2. METHODS OF INVESTIGATIONS – TOOLS AND EQUIPMENT

The major goals of both the experiments and simulations were the demonstration of the efficiency of the proposed techniques. The optical tools and instruments were chosen so that their parameters would be as close to state-of-the-art stepper parameters as possible. He-Ne, He-Cd and Ar-ion lasers were used as light sources that illuminated the mask (a simple pinhole, USAF test target or industrial mask produced by Texas Instruments Inc.). A Tropel CL-100 scanning Fabry-Perot interferometer inserted behind the mask was controlled by piezo translators. Microscope objectives and an industrial stepper lens (5116g Tropel) were used as magnification and projection lenses, respectively. The final image was captured by a COHU CCD camera.

Simultaneously with experimental evaluation, simulations were provided by Prolith/2 and Solid-C, microlithographic simulation tools.

3. SCIENTIFIC RESULTS

2. A combination technique of interferometric phase shifting and off-axis illumination was detailed. The experimental and theoretical results agreed well, and showed that the proposed technique could improve the resolution by 30% for line/space patterns. The issue of image contrast degradation introduced by two-beam imaging could be addressed by the satisfaction of the following two conditions:

Amplitude Condition: The peak intensity of the transmitted pattern must be equal to the minimum intensity of the reflected pattern.

Phase Condition: The phase difference between *R* and *T* images must be π, i.e. the images must be in the opposite phase.

and the image contrast could achieve the maximum 100% value.

Since in the proposed arrangement no beam splitter was placed between the mask and the projection lens, optical aberrations could not cause such serious problems as in the original phase shifting setup. [1,5-8,20]

2. Resolution improvement of 52% was demonstrated experimentally using a single on-axis hole by means of an annular aperture. Simulation and experimental evaluation of the imaging of extended hole arrays and other feature types is necessary for a detailed final conclusion. On the other hand, experiments should follow the trend of optical microlithography and shrink the wavelength to 248 nm. Preliminary experiments performed at 248 nm show that the main issues that have to be solved are:

- pulse to pulse instability of excimer lasers,
- vibration sensitivity of the system,
- efficient focal position alignment. [9,24]

3. The three-dimensional aerial image of an on-axis contact hole was calculated and optimized using a wave optics model by means of a coated objective. The optimum obstruction ratio was found to be ε=0.3. In addition to the results of a scalar wave optics model, a microlithographic simulation tool Solid-C was used to calculate the aerial image of contact hole arrays. It was shown that an appropriate coated objective could enhance the *DOF* by a factor of 1.5 to 2. The focus-exposure process window becomes significantly larger, even if the designed feature size on the resist is below the theoretical Rayleigh limit. [15,24]

4. The aerial image of an on-axis point-like source was calculated using a scalar wave optics model when a birefringent plate was inserted between the projection lens and the wafer. The plate shifts the foci created bythe ordinary and the extraordinary rays to different amounts. The distance between these images can be controlled by the thickness of the plate, and strongly depends on the refractive index. Since aberrations proportional to the thickness of the plate cause undesirable distortions, the application of a thin but strongly birefringent material is a better candidate than using a slightly birefringent but thick plate. [15]

5. A novel multiple imaging technique based on the application of a Fabry-Perot etalon was demonstrated experimentally. The distance and the amplitude ratio between the adjacent images could be controlled by the separation and the reflectivity of the etalon mirrors, respectively. The depth of focus and resolution were improved by a factor of 4 and 1.6 using an on-axis point-like source. [2, 3, 10-14, 16, 17, 21-23]

6. It was shown theoretically that a Fabry-Perot etalon placed between the mask and the projection lens can be considered as a spatial filter that transmits certain spatial Fourier components of the mask pattern, while blocking others. Based on this analogy, the proposed multiple imaging technique could be simulated by means of an appropriate pupil-plane filter. [4]

7. The point spread function of the optical system was calculated using Prolith/2 and compared with the experimental results. [4,18]

8. Spatial coherence of the optical system was optimized for contact hole arrays. The optimum value was found to be σ=0.28. [18,19]

9. The aerial images of extended mask patterns (off-set contact hole arrays and line/space patterns) were evaluated experimentally and theoretically. Light loss, pitch sensitivity and increased intensity side lobes introduced by the filter were also evaluated and effective methods were proposed to minimize their undesirable effects. [18,19]

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