Microcircuit Engineering

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PREFACE

Microcircuit engineering covers novel aspects of the fabrication and inspection of integrated circuits and very small solid-state devices. It is a branch of electronics in which there has been an enormous growth in the last decade as device sizes have been dramatically reduced to the extent where dimensions of a few μm seem large. As the feature size has decreased the circuit chip has become more complex, while concurrently prices have fallen sharply as a result of technical advances and the unique mass production methods used by the modern semiconductor industry.

The advantages of scaling down the device dimensions were first realised by illuminating patterns on to photoresist coated silicon wafers. The limits of this, now conventional u-v light lithography, were anticipated with the development of techniques that use deep u-v light, x-rays or electron beams to fabricate features with dimensions of 1μm or less. These new techniques have brought research projects in system design, alignment of patterns, limits of performance, resolution and speed of electron resists into laboratories and production plants. The results of the work offer the prospect of scaling dimensions by an order of magnitude below the limits of conventional u-v light methods. The impact of such a reduction on computers, memories and digital systems could be very significant.

Research on microcircuit engineering has been pursued in laboratories in many countries. Notable advances have been made in the industrial research laboratories of IBM, Hughes, Bell Laboratories and Texas Instruments in the U.S.A., in Thomson-CSF of France, the VLSI Co-operative Laboratories in Japan, Philips and Cambridge Instruments in England to mention just a few. The work at Cambridge University's Engineering Department on scanning electron microscopy has continued for many years and has led not only to its own research group's contributions in electron beam lithography but through its ex-research students has contributed to the work in many laboratories in the U.S.A. and the U.K.

Conferences have been held in the U.S.A. on electron, ion and photon beam technology for many years and have been a valuable and successful forum for reporting the most important research achievements. The first meeting on the subject in Europe was held in Cambridge in 1975 and was followed by meetings in Aachen in 1976 and Paris in 1977. In 1978 the meeting again returned to the Engineering Department of Cambridge University with the title of "Microcircuit Engineering" and with the prospect of becoming a regular meeting in Europe. Many of those who contributed and attended took the opportunity to visit their first research laboratory again and there were occasions for a considerable exchange of views and ideas on the subject.

The meeting was organised so that each of its sessions was introduced with a substantial review paper, and followed by several papers of detailed current research work and these have all been gathered together in this book. The review papers form a valuable introduction to the subject for anyone entering the field of microcircuit fabrication and inspection while the individual papers highlight the areas of most active research. There are sections with comprehensive reviews on electron beam lithography, x-ray lithography, electron resists, optical methods and inspection methods. The book as a whole will be of interest to current research workers in microelectronics and also to those newly entering the subject. It introduces the reader to the subject and it is also a record of some of the main advances in the electronics of microfabrication and microcircuit inspection.

In editing this book it is a pleasure to acknowledge our gratitude to those who presented their work at the conference and contributed papers for publication; to the Institute of Physics and particularly Clive Jones who helped so efficiently with the arrangements, the many members of the Engineering Department who helped with the organisation and running of the conference; to our secretaries who helped to organise the conference and type the manuscripts, Gillian Hotchkiss, Janis Eagle, Priscilla Reynolds and Janet Thompson; to John Sackett and Nitin Shah who prepared the index and read proofs with us; and finally to Cambridge University Press who have made the presentation of the book so attractive.

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HIGH RESOLUTION LITHOGRAPHY

FOR MICROCIRCUITS

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INTRODUCTION

There is a continuing trend in microcircuit engineering towards increased circuit complexity and reduced pattern dimensions. In order to meet these developments, the need has arisen for new lithography systems with better performance than existing optical systems.

Lithography is the art of defining the intricate patterns needed for the fabrication of microcircuits. In general, several patterning steps are needed for any integrated circuit or device. Take the relatively simple case of FET, a minimum of four patterning steps are required: one for defining the active area of the device, one for the gate, one for the contact holes, and finally, one for the metallization. Figure 1 shows the principle of these four steps. For more complex devices it is not uncommon to need ten or more such steps. Each of these patterns has to be carefully delineated and accurately aligned with the other levels.

These intricate patterns are formed by coating the wafer with a layer of resist which is a thin film of light sensitive organic material. An ultra-violet (UV) light image is then imprinted into this layer traditionally by contact printing through a mask engraved with the pattern. Alignment of the mask to the wafer is achieved by viewing features on the wafer - known as registration marks - through special windows in the mask. Yellow light is used during alignment in order to avoid exposing the resist. This contact printing technique is well established, simple and low cost, but has the following limitations which restrict further progress:

i. The smallest structures that can be made are limited to lateral dimensions of about 2μ by diffraction effects which occur between mask and wafer. Diffraction also limits the accuracy with which one pattern can be aligned to another.

ii. The percentage of good devices made is limited by damage which results from bringing the mask and wafer into close proximity.

Several new methods are being explored to overcome these problems. The methods can be broadly divided into three categories: A) extensions of optical contact/proximity printing methods using shorter wavelength radiation; deep UV, and soft X-ray; B) optical projection systems which can be either full-field scanning or step and repeat, C) electron beam methods which can be either scanning or projection.

The ways in which these approaches can be utilized in a microcircuit manufacturing environment have been extensively discussed (Broers, A. N., 1978; Gordon and Herriot, 1975). They are summarized in Figure 2.

This paper briefly describes the principles of the different methods and discusses their advantages and disadvantages for different applications. Scanning electron beam systems are treated in more detail than optical and electron beam projection systems and x-ray lithography because reviews of these subjects appear elsewhere in this volume.

1. CONTACT/PROXIMITY PRINTING

Contact printing remains a widely used wafer exposure technique in the microelectronics industry. Today masks are more often "hard-surface", typically chromium on glass, rather than photographic emulsion, but the basic ultra-violet (UV) contact printing process has remained the same for many years. In some instances a small gap is maintained between mask and wafer in order to reduce mask damage and to eliminate the picking up of resist from the wafer onto the mask. In this case the term proximity printing is often used.

As mentioned earlier, the major drawbacks of contact or proximity printing are the low yield it produces due to mask/wafer damage, the need for an expensive mask with a short life, and limited resolution. Diffraction effects and alignment considerations between mask and wafer typically limit minimum linewidths to a few microns. When critical mask alignment is not required, such as for magnetic bubble devices, dimensions of less than 2μ have been produced even in manufacturing processes.

1.1 Deep UV Lithography

Resolution in contact printing can be improved by reducing the wavelength of the exposing radiation (Lin, B. J., 1976; Lin, B. J., 1975) and by reducing the spacing between mask and wafer (Smith, H. I., 1969; Smith, H. I., et al., 1974). Deep UV radiation (2000-2600Å) has been used successfully in combination with conformal contact between mask and wafer to produce 0.5μ linewidths (Lin, B. J., 1976). Figure 4 shows the resolution that can be realized by using conformal printing and deep UV illumination. Figure 3 is a diagram of the mask-wafer chuck used to obtain this result. Conformal printing can be performed if either the mask or the wafer is thin.

For deep UV radiation, resists originally developed for electron beam exposure are used instead of photoresists. The mask is aluminum or chromium on quartz and is made with a scanning electron beam system. A mercury arc is used as the illumination source, and exposure times of a few minutes for a 3" wafer can be obtained with suitable illumination optics. The wavelength range used for exposure is determined at the upper end by the electron resist which is insensitive above about 2600 Å, and at the lower end (2000 Å) by lack of transmission through the quartz optical components and the mask substrate.

Although this method offers very high resolution, it will be difficult to apply it to semiconductor production because mask-wafer damage remains a problem. There may be significant advantages to be gained, however, by using deep UV radiation and electron resist without the need to bring mask and wafer into contact. For example, it should be possible to obtain 1.25μ linewidths with a mask to wafer spacing of 4-6μ (Lin, B. J., 1976). For surface acoustic wave devices, integrated optics, and some single layer magnetic bubble devices where the benefits of simplicity, high resolution and favorable resist profiles are important, it may be advantageous to tolerate a moderate yield loss and use the conformal printing process.

Multilevel micron or submicron devices have not been fabricated with this technique so it is not possible to assess whether adequate overlay accuracy can be obtained in a manufacturing process. This problem and the fact that silicon wafers distort both laterally and vertically when they undergo hot processes (such as recessed oxide growth) are additional difficulties preventing the immediate application of this technique to integrated circuit production. They also apply to x-ray lithography.

1.2 X-Ray Lithography

X-ray lithography is contact/proximity printing using soft x-ray radiation (λ = 4-50Å) rather than UV(λ = 2000-4000Å) radiation. The quartz mask substrate is replaced with a membrane which is thin enough to transmit the exposing radiation and yet thick enough to be dimensionally stable. Membranes of silicon, mylar, polyimide, aluminum oxide, silicon nitride and silicon carbide have been explored. The absorber pattern is formed generally with a scanning electron beam system from a high atomic weight metal which heavily absorbs the incident x-rays such as gold, palladium, or hafnium.

Figure 5 shows the basic principle of the x-ray technique. Although basic feasibility of the method for pattern exposures has been established, much work remains to be done to find the best combination of substrate material, substrate thickness, absorber material, absorber material thickness, and the wavelength of the x-ray radiation.

The most remarkable feature of x-ray lithography is that pattern definition is preserved deep into the resist. This is clearly demonstrated by the 1μ linewidth obtained in an 8μ thick resist layer, shown in Figure 6 (Spears, D. L. and Smith, H. I., 1972 (a); Spears, D. L. and Smith, H. I., 1972 (b); Smith, H. I. et al., 1974; Spiller, E. et al., 1976 (a); Spiller, E. et al., 1976 (b); Maydan, D. et al., 1975; Feder, R. et al., 1976; McCoy, J. H. et al., 1974). The resist is believed to be exposed (polymerized or depolymerized) by photoelectrons produced by the x-ray photons and not by the x-ray photons themselves. X-ray photons are not scattered in the way electrons are scattered, and the photoelectrons have little range in the resist because their maximum energy is only equal to the incoming photon energy (280-1500 eV). The exposed pattern, therefore, does not become blurred by scattering as is the case with electron exposure, or by diffraction as in UV exposure.

In the limit the range of the photoelectrons determines the edge sharpness. This is about 600 Å for rhodium radiation (λ = 4.6 Å), 400 Å for aluminum radiation (λ = 8.3 Å) and 50 Å for carbon radiation (λ = 44.8 Å). For high resolution it is obviously better to use softer radiation, but this requires a very thin mask substrate which is difficult to handle and may not be dimensionally stable. Shorter wavelengths and thicker substrates will give better mask stability and may therefore be advantageous, where minimum linewidths are relatively large. Another advantage with x-ray exposure is that dust particles on the mask are generally transparent to the x-rays and do not create as serious a problem as they do with UV masks.

Exposure speed remains a problem with x-ray lithography, but recently improvements have been made in source output and resist sensitivity. Typically negative x-ray resists have a sensitivity of 10 to 500 mJ/cm^2 and positive resists, a sensitivity of 10-1000 mJ/cm^2 (11). Conventional sources with rotating anodes operate with several tens of kW of electron beam power. It must be remembered that, as with all resist processes, the sensitivity has to be defined in terms of the resist (wall) profile and the acceptable thickness loss in the resist areas which remains after development (Hatzakis, M., 1975).

Methods for aligning mask and wafer have been investigated in several laboratories (Maydan, D. et al. 1975; McCoy, J. H. et al., 1974; Hatzakis, M., 1975; Flanders, D. C. et al., 1977; Austin, S. et al., 1978). They utilize UV illumination, transmitted x-rays, characteristic x-rays, or photoelectrons to detect sample position. All are feasible from a theoretical point of view given adequate time, but the most promising relies on the detection of asymmetries in the combined diffraction maxima formed from reference gratings on mask and wafer when the marks are illuminated with a laser (Flanders, D. C. et al., 1977; Austin, S. et al., 1978). Misalignments of less than 0.1μ have been detected. The next step is to show that this accuracy can be maintained over a full wafer and that the overall alignment process can be achieved without a significant increase in the cost of the process. Overlay errors arising from lateral distortion of the sample or from lack of sample flatness (see Figure 5) also have to be investigated before a clear commitment to use x-ray lithography for semiconductor devices can be made. It should be possible to overcome these errors by using a step and repeat approach, but this would require significant improvement in exposure speed and may necessitate the use of the storage ring as discussed in the following paragraph. As with deep UV printing, x-ray lithography can already be used to advantage for single layer processes.

The ultimate source of x-rays from the point of view of throughput is the electron storage ring (Spiller, E. et al., 1976; Lindau, I. and Winich, H., 1978; Yamazaki, S. et al., 1978). The radiation is so intense that it has been estimated that typical industrial throughput requirements could potentially be met by a fraction of the output from a storage ring in which the stored current is in excess of a few tens of milliamperes. Another advantage of synchrotron radiation is that it is highly collimated (divergence 10^{-3} radian). This means that pattern distortion errors which arise when the substrate is not flat are no longer as important as they are for a conventional point source placed close to the sample. The major problems with the storage ring are high cost and 'overcapacity' which will make it difficult to use efficiently. Recently, new developments have been made in the use of high power laser x-ray sources (Peckerar, M. C. et al., 1978). While these may have good potential, they are still in their early stage of development.

2. OPTICAL PROJECTION

Two forms of optical projection have been developed for semiconductor device fabrication. They are 1:1 scanning projection and step and repeat reduction projection. Their main advantage over contact or proximity printing is that mask and wafer are completely out of contact and the potential for damage is eliminated. They may also offer improved resolution and overlay accuracy in manufacturing situations.

2.1 1:1 Optical Projection

Several 1:1 scanning optical projection systems have been proposed (Markle, D. A., June 1974; CA 3000 Projection Alignment System built by Cobilt Division, Computervision, Santa Clara, California, U.S.A.; Cuthbert, J. D., August 1977; Dill, F. H. et al., June 1978). The most widely used system is shown in Figure 7 (Markle, D. A., June 1974). This system operates at unity magnification and utilizes a mirror lens system. Only a crescent of the mask is illuminated at one instant, and this portion of the pattern is transferred to the sample with a parity that allows mask and wafer to be scanned in the same direction and therefore to be mounted on a single holder. The entire wafer is exposed in a single scan. The magnification of the mirror optical system is 1X so the mask has the same dimensions as the pattern. The resolution at this time is adequate to reproduce 3μ linewidths, or comparable to conventional UV proximity printing. Alignment accuracy is reported to be ±1μ and the depth of focus is relatively large (±5μ for 2μ lines and ±12.5μ for 3μ lines) compared to reduction projection systems. This is because partially coherent illumination is used. The influence of partial coherence has been discussed by several authors (Cuthbert, J. D., August 1977; Offner, A., May 1978). The mirror imaging system does not have chromatic aberrations, and a broad spectrum of radiation from the mercury arc is used to expose the resist. This produces an exposure time under a minute with a minimum of 6 seconds. Time for manual alignment must also be considered when estimating throughput. A full description of the system is given in reference (Markle, D. A., June 1974).

New systems of this type are under development with improved optics, automatic alignment, better mechanical tolerances and tighter temperature control. When combined with the use of deep UV radiation and compatible resists, significant improvements in resolution and overlay accuracy (±0.25μ) have been predicted (Offner, A., May 1978).

1X scanning systems are full-wafer exposure systems and will encounter severe overall dimensional stability problems as dimensions approach 1μ. The numerical aperture of the mirror imaging system will also have to be increased from the present value of 0.16 to about 0.3, and even with partially coherent illumination, depth of field will become very small. This may be intolerable because it will be very difficult to adjust focus and to level the sample for different positions on the sample surface.

The cost/throughput ratio is favorable for the 1:1 scanning optical approach because exposure time is short and because only one alignment is required for each sample.

2.2 Step and Repeat Reduction Projection Systems

Step and repeat reduction projection systems similar in principle to that shown in Figure 8 have been used for years to produce master masks for contact printing. Demagnifications between 4X and 10X are used between mask and wafer. The mask has larger dimensions than the final pattern, and dimensional tolerances can be relatively easily met. Advanced systems of this type have recently been built in several laboratories (Tobey, W., August 1977; Wittekiek, S., May 1977; Lacombat M., 1977; FPA141 Projection Mask Aligner built by Canon Inc., Kawasaki, Japan). They have demonstrated higher resolution than the scanning systems; however, when this resolution is required the field size is much smaller than the sample and exposure has to be made in a step and repeat manner. For 1μ dimensions the maximum field diameter that has been achieved with adequate contrast for resist exposure (MTF = 60%) is 1.4 cm. (Wilczynski, J. S. and Tibbetts, R., 1976; 1969). In this instance the lens has eleven elements and is assembled with an accuracy that is close to presently achievable limits. In order to cover the entire sample, the sample is mechanically stepped between exposure sites. The depth of focus for the case of 1μ linewidth is very small (about ± 1μ), which makes refocusing for every chip essential. Accurate sample levelling is also required. As with the scanning optical system, depth of field can be improved by employing a partially coherent illumination system. This may, however, introduce problems in linewidth control because the intensity at the edge of pattern features no longer falls off monotonically and fringe effects have to be considered (Cuthbert, J. D., August 1977; Dill, F. H. et al., 1975). Exposure time per field can be less than a second despite the need imposed by the lens chromatic aberration to use narrow band illumination.

Current step and repeat systems have used two forms of alignment. In the first case an initial mask to wafer alignment is made and an accurate laser interferometric system is used to keep track of the sample during the stepping process. Systems of this type have relatively high throughput because only one alignment is required per wafer. For example, the Mann 4800 (Mann 4800 manufactured by CICA-Mann Corp., Burlington, Mass., U.S.A; Roussel, J., May 1978) camera exposes 50 7.5 cm diameter wafers per hour (0.3 sec. exposure, 0.3 sec. table stepping) with a minimum linewidth below 2μ and an alignment accuracy better than ± 0.5μ.

In the second case a mask to wafer alignment is performed for each chip site. This alignment can in principle be automatic and correct for rotational errors as well as offset errors, thus relaxing the required mechanical tolerances for the S/R table. A system which aligns at every chip will also compensate for any wafer distortion errors which might occur due to hot processing and/or wafer chucking. An overall accuracy ± 0.25μm may be achievable in this case and if the alignment process is automated, the loss in throughput may be acceptable.

In principle the resolution of a reduction projection system should be adequate to fabricate linewidths approaching 1μ and promising test exposures have been reported (Hugues, M. et al., 1977). An example of the resolution obtainable in recent exposures by this type of system is shown in Figure 9. Suitable resist processes must be found, however, and adequate linewidth control on real samples which have non-flat surfaces may be difficult to achieve.

3. ELECTRON BEAM SYSTEMS

Electron beam lithography methods were first pursued in the late 1950's for their high resolution capability (Mollenstedt, G., 1961). It was very soon recognized, following the successful development of the scanning electron microscope (Oatley, C. W. et. al., 1965) that electron beam systems also offer the ability to directly generate patterns at high speed and with great pattern flexibility. The first manufacturing electron beam systems were built to take advantage of this attribute rather than the high resolution. They were built for mask-making and for custom interconnection of integrated logic circuits at dimensions compatible with optical lithography. Recently both advantages have been combined in the laboratory to produce full complexity integrated circuits with dimensions below 1μ. See, for example, the 0.6μ channel length FET structure shown in Figure 10b. This is an extension of the 1.25μ channel 8K FET RAM described in reference (Yu, H. N. et al., 1975). Exposure speed is already at a level at which the method is economically attractive in many environments, and potential exists for further improvement.

Electron beam projection systems have been studied because they offer the potential for higher exposure speed and lower cost than scanning systems. The difference in cost has been considerably reduced by advances in scanning systems, but a potential advantage for projection systems still remains for memory devices where the high speed pattern generation ability of the scanning systems is not needed. Flys' eye lens systems (Newberry, S. P., et al., 1967; Heynick, L. N. et al., 1975; Parks, H.G. and Hughes, W.C., May 1975) have also