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EXPERIMENTS ON X-RAY LITHOGRAPHY USING SYNCHROTRON RADIATION FROM THE VEPP-2M STORAGE RING

E.S. GLUSKIN, A.A. KRASNOPEROVA, G.N. KULIPANOV, V.P.NAZ'MOV, V.F. PINDJURIN, A.N. SKRINSKY and V.V. CHESNOKOV

Institute of Nuclear Physics, 630090, Novosibirsk 90, USSR

During the last few years the electron–positron storage ring VEPP-2M of the Institute of Nuclear Physics in Novosibirsk has been used as an efficient source for X-ray lithography in the intermediate wavelength range ($\lambda \sim 10$ Å). Selection of the required part of the SR spectrum is done by means of a mask substrate fabricated from silicon of 2 μm thickness; Al windows can be installed before the X-ray mask. Exposures can be made in vacuum or in helium.

The lithographic system can be used to fabricate one-layer devices on 100 mm diameter wafers with a production rate of 10–12 wafers per hour. The influence of the geometric conditions and of various temperature modes of exposure on the precision of replication from the mask onto the resist film have been investigated. Parameters of several X-ray and electron resists are studied.

A lithographic system for fabricating multilayer devices is being developed. At present near to the storage ring a special room with clean-room environment is being built. Two SR beam lines come into it. The first beam line brings SR from the bending magnet. In the future the second beam line will bring SR from the special "lithographic wiggler". In this room all operations on wafer preparation, subsequent processing steps of resist and masked surfaces after X-ray lithography and control of the patterns obtained will be carried out.

1. Introduction

X-ray lithography is a promising technology which can find wide application in the production of integrated circuits with elements of submicron size.

This technology is being extensively developed in various laboratories and the results obtained before 1977 are described most completely in the review by Feder and Spiller [1]. In recent years the prospects for using X-ray lithography are mainly connected with application, in this technology, of synchrotron radiation (SR) generated by a charged particle storage ring [2–4].

At the Institute of Nuclear Physics (Novosibirsk) the storage ring VEPP-2M has been used in X-ray lithography experiments for several years. In the present paper, the main results of these experiments are reported and the requirements of a radiation source which is suitable for producing integrated circuits with elements of submicron size are briefly analysed.

2. Description of a station for X-ray lithography

An X-ray lithography station which utilizes the SR from the storage ring VEPP-2M at energies from 500 to 670 MeV has been designed. The spectral distribution of the VEPP-2M synchrotron radiation with $E = 650$ MeV is depicted in fig. 1 (curve 1). The radiation intensity is a maximum at a wavelength of 10 Å. After integration over the whole spectral range and the vertical angle, the radiation power of this sources is 70 mW at $E = 500$ MeV ($I = 0.1$ A) and reaches 300 mW at $E = 670$ MeV ($I = 0.1$ A) per mrad of horizontal angle.

The X-ray lithography station consists of the following main components (fig. 2): a vacuum SR channel and an exposure chamber. The SR channel is equipped with various gating (2,6) and fast (7) valves and a shutter (5) which cuts off the SR beam. The SR can be extracted both in vacuum and in a helium atmosphere. In the

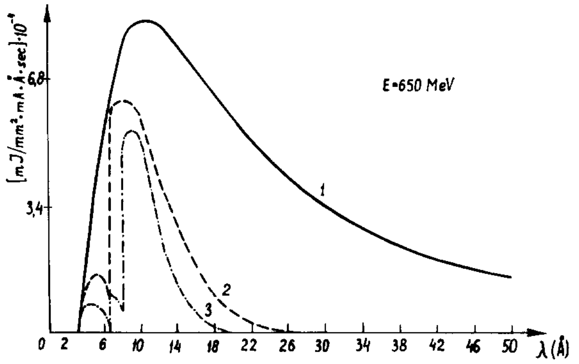

Fig. 1. Spectral distribution of synchrotron radiation from VEPP-2M; 1: without filters; 2: behind Si filter (thickness 1.8 μm); 3: behind Si (1.8 μm) and Al (1 μm).

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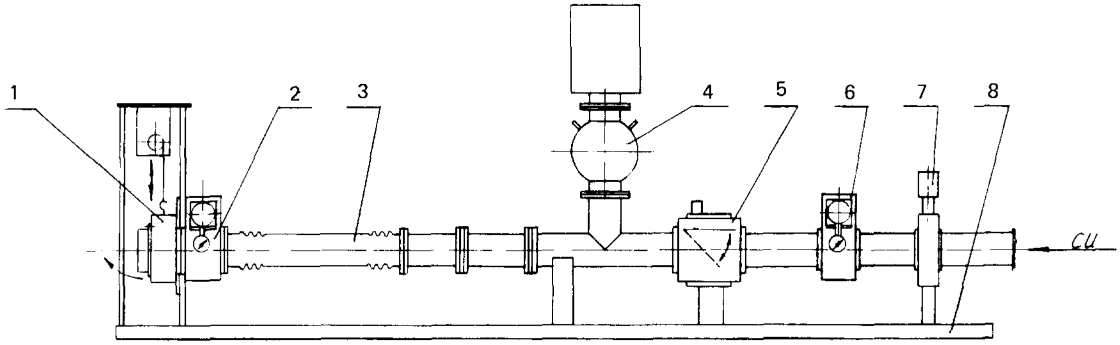

Fig. 2. Scheme of lithographic station.

latter case, a set of filters, which consists of two Al foils of 10 × 80 mm^2 area and 1–2 μm thickness, is installed. In the exposure chamber (1) there is one holder with an X-ray mask and the wafer to be exposed. The design of the holder provides a constant gap between the mask and wafer of 100 μm. The chamber volume is not large and this makes it possible to replace the holder, evacuate the chamber to 10^{-6} Torr, or to fill it with helium within 5 min.

The X-ray mask employed is a Si film of about 2 μm thickness and 80 mm diameter with an outer base ring. The membrane is supported by a frame made of gold deposited by electroplating; absorbing elements of 0.3–0.5 μm thickness on the membrane are also deposited in this manner. The spectral distribution of radiation (with $E = 650$ MeV) behind the Si film of 1.8 μm thickness is given in fig. 1 (curve 2). Curve 3 in this figure demonstrates the spectral distribution of the radiation passed through the 0.1 μm thick Al window and through the Si film of the X-ray mask. It is seen that these filters effectively transmit the radiation in the range from 5 to 15 Å with a maximum of about 8 Å. The contrast of the X-ray mask varies between 14 (at Au thickness of 0.3 μm) and 45 (at an Au thickness of 0.5 μm) with $E = 650$ MeV. For 500 MeV energies the contrast is higher: 19 and 137, respectively. The absorbing pattern on the X-ray mask is fabricated by means of an electron beam and projection photolithography and has a structure in the form of squares and lines of thickness 0.3 μm or thicker . In the chamber the horizontal size of the SR beam is determined by the inner diameter of the SR channel and is equal to 95 mm. The vertical size of the SR beam at halfheight intensity, equals 10 mm (for radiation with $\lambda = 10$ Å and a distance of 7 m from the radiation point). A sample of large area can be irradiated by scanning the chamber in the vertical direction. The exposure chamber is placed in a box with a dustfree environment; the holders are in the same box. The X-ray lithography station operates on-line with a computer "Electronica-60".

3. Results

The optimum mode of operation of the X-ray lithography station described above has been chosen. The study of the characteristics of negative X-ray resists has demonstrated that the contrast of the X-ray mask, equal to 14 ($E = 650$ MeV, Al thickness 0.3 μm) is not sufficient to obtain good-quality profiles of replicated pattern because the portion of radiation which passes through the layer of gold on the X-ray mask, polymerizes the underlying parts of the resist. This makes it impossible to develop a pattern through the total thickness of the resist. Negative resists have been studied at $E = 500$ MeV; the integral transmission coefficient of the X-ray mask membrane was 0.04. The sensitivities of the negative resists studied range from 3 to 12 mJ/cm^2. The sensitivity of a resist is defined as dose corresponding to the beginning of saturation of the characteristic curve. Characteristic curves for three types of negative resists are presented in fig. 3. The resolution of negative resists was usually about 1 μm. This limits their application.

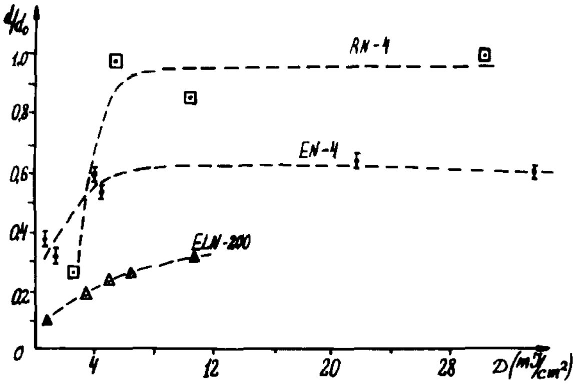

Fig. 3. Normalized remaining resist thickness for negative resists versus exposure.

Positive resists have been studied at $E = 650$ MeV; the integral transmission coefficient of the X-ray mask film is equal to 0.19. The resists studied had sensitivities from 19 to 1000 mJ/cm^2. The sensitivity of positive resists was defined as the dose necessary for complete development of the exposed parts. Characteristic curves for two types of positive resists are presented in fig. 4. The patterns obtained with positive resists, are shown in fig. 5. The positive resist EP-1 has the best resolution. Fig. 6 demonstrates the pattern with 0.3 μm linewidths obtained with this resist. The time necessary to exposure completely the resist EP-1 (at $E = 650$ MeV, $j = 0.1$ A) is about 12 s. It is clear that the exposure of a wafer of 80 mm diameter takes about 1.5 min.

The high power of the storage ring SR leads to a considerably heating of the X-ray mask. As a result, the replicated pattern will be misaligned with the respect to patterns of subsequent layers because of the difference in the thermal coefficients of expansion of the X-ray mask and resist materials. If the accuracy of layer alignment should be not worse than 0.1 μm for wafers of 80 mm diameter, the temperature should be stabilized within 1°C. In such cases, helium is utilized as a thermal exchange gas.

Temperature measurements for a Si X-ray mask exposed to the SR beam have been carried out. Temperature was measured with a thermocouple at the centre and the edge of the X-ray mask. The 80-mm-diameter X-ray mask used had a Si film of 2 μm thickness with a pattern made of Au of 0.5 μm thick. Rigidity of the film was provided by the nonetched Si framework of 0.5 mm width. The framework formed a grid with 5 × 5 mm^2 cells; the thermocouple was placed at the point of intersection of the grid on the side opposite to the incident radiation. The X-ray mask was either stuck to the holder along the outer ring (the version of holder I), or was pressed to it by a massive metallic ring. The measurements were carried out with $E = 660$ MeV, $j = 40$ mA under the following conditions: a) in vacuum without filters and using versions of holders I and II; b) in vacuum with the use of Al filters of 3–4 μm thick-

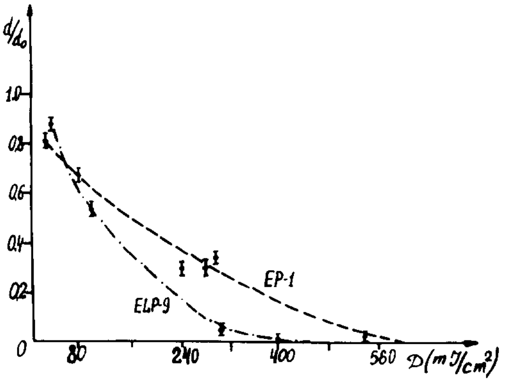

Fig. 4. Normalized remaining resist thicknesses for positive resists versus exposure.

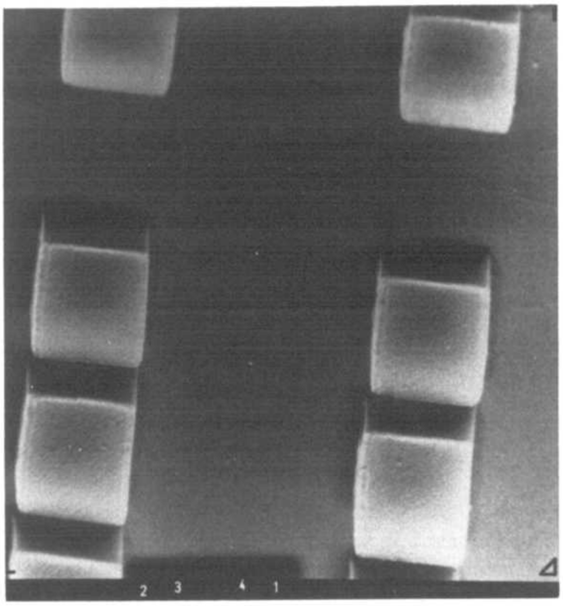

Fig. 5. Resist patterns obtained with positive resist.

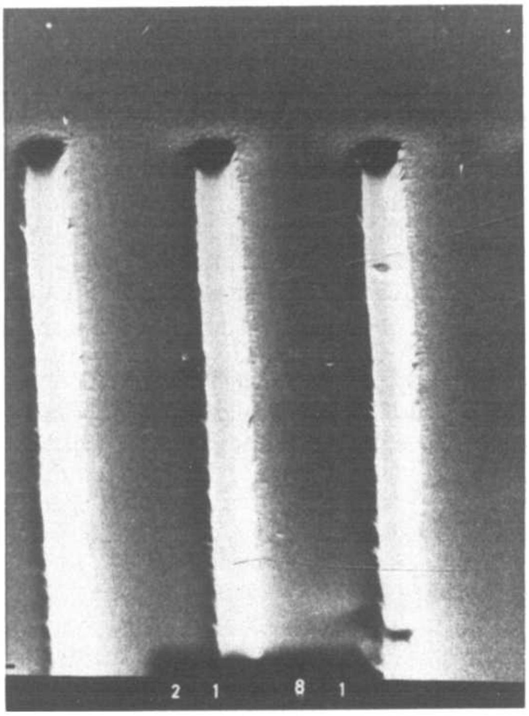

Fig. 6. Resist patterns of 0.3 μm linewidth obtained with EP-1 resist.

Table 1
Results of measurements of temperature of X-ray masks

Conditions:	Vacuum, version of holder I		Vacuum, version of holder II		Vacuum, Al filter centre	He atmos., Al filter centre
	centre	edge	centre	edge		
T[°C]	21	21	12	2	0.7	0.26
t[s] [a)]	360	360	260	260	80	20

[a)] t is the time taken to establish a constant temperature (T) of the framework of the X-ray mask.

ness; c) in helium under a pressure of 3 Torr. In cases b) and c) the dimension of the SR beam incident on the X-ray mask was 10 × 10 mm^2. The results of measurements are listed in Table 1.

The temperature of the Si film is of interest and simple estimations show that it exceeds the temperature of the framework by 10°C under exposure in vacuum without filters and by 0.8°C under exposure through an Al filter.

The results obtained point out that in order to attain an accuracy of image replication not worse than 0.1 μm on wafers of 80 mm diameter, it is necessary to operate in a helium atmosphere. When replicating patterns with 1–2 μm elements on a large area, or submicron elements on a small ($\sim$ 1 cm^2) area, it is then only to use filters which remove a significant part of the heating from the X-ray mask.

The station described above is suited for multiplication of X-ray masks, for fabrication single-layer devices. The alignment system, which is being designed, will allow this station to be employed for multilayer lithography. The experience of using this station has shown that in order to reduce the level of defects in the process of X-ray lithography, the operations that are connected with preparation of the wafers with resists and of the X-ray mask and subsequent processing steps should be performed in the close vicinity of the X-ray lithography station. In view of this, a special room for two new SR channels has been built near the storage ring. One channel is intended for the radiation from the bending magnet and the second is intended for the radiation from a special "lithographic wiggler". In the same room there is a support facility, which includes the equipment for wet chemical etching of wafers, centrifuge for X-ray resist deposition and also the equipment for development and IR-drying, for chemical plasma etching, optical microscopes for the control of patterns. So, the whole cycle of operations dealing with the preparation of wafers, exposure, subsequent processing steps and control of resistive layers will be performed in the same clean room. This is expected to lead to a decrease in the level of defects at the X-ray lithography station.

4. Analysis of the X-ray lithographic scheme

The main experiments at the X-ray lithography station have been performed with the view of obtaining replications of 2–3 μm in size. In the following, the X-ray lithography process in the submicron region is assumed to be used. In connection with this, it is of interest to determine the requirements for a source of radiation, which is capable of providing the integrated circuits with submicron elements at a rather high rate of productivity.

The source parameters of great importance for lithography are: the source brightness, the size of the spot and the spectral composition of the radiation.

Let us formulate the requirements for the spectral composition of the radiation. The optimum wavelength λ for resolution δa, can be found from the equation

$$\delta a^2 = \lambda L_2 + (0.35/\rho\lambda)^2. \qquad (1)$$

Here L_2 is the gap between an X-ray mask and the wafer (see the lithography scheme in fig. 7), ρ is the density of the resist material. The first term is a diffraction broadening of the pattern, the second one is the "smearing" which is caused by the secondary electrons. These electrons are produced in the resist material during interaction of it with the X-ray quanta (the numerical coefficient in the second term is taken from ref. 5).

It follows from eq. (1) that the optimal wavelength at

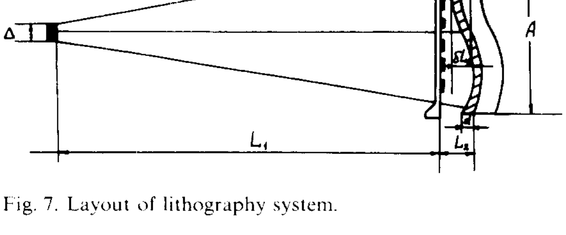

Fig. 7. Layout of lithography system.

a given spatial resolution is equal to:

$$\lambda_{\text{opt}}(\text{Å}) = \frac{0.48}{\rho(\text{g/cm}^3)\,\delta a(\mu m)}. \tag{2}$$

In this case, the size of the gap is limited by the quantity $L_{2\max} = 2.8 \times 10^4 \rho(\text{g/cm}^3) \cdot \delta a^3(\mu\text{m})$ [3].

The dependences $\lambda_{\text{opt}}(\delta a)$and $L_{2\max}(\delta a)$ are given in fig. 8.

Let us consider the requirements for the brightness of the source. An equation for exposure time t can be written as follows:

$$\frac{B \cdot \Delta^2}{L_1^2} \cdot \delta a^2 \cdot t = \frac{\bar{n}}{\eta(1 - e^{-\mu d})} \cdot \frac{d}{\delta a}, \tag{4}$$

where the number of photons, emitted by a source with brightness B and falling on a site of area $\delta a \times \delta a$ in size, is presented on the left-hand side. On the right-hand side, both the losses because of incomplete absorption of photons in the resist film of thickness d and with efficiency η for the photochemical conversion in the resist material. μ is the absorption coefficient in the resist, $\bar{n}$ is the sensitivity of the resist, expressed in the number of photons absorbed by the element of volume δa^3, which are necessary for complete development of the resist. The latter quantity has the limitation in principle, which is associated with the statistical nature of the absorption process [1]. The distance L_1 between the source and the X-ray mask should be optimized, proceeding from the required resolution δa. Taking into account the errors in sizes, which is connected with the finite size of the source, $\delta a = \Delta \cdot L_2/L_1$, and with the

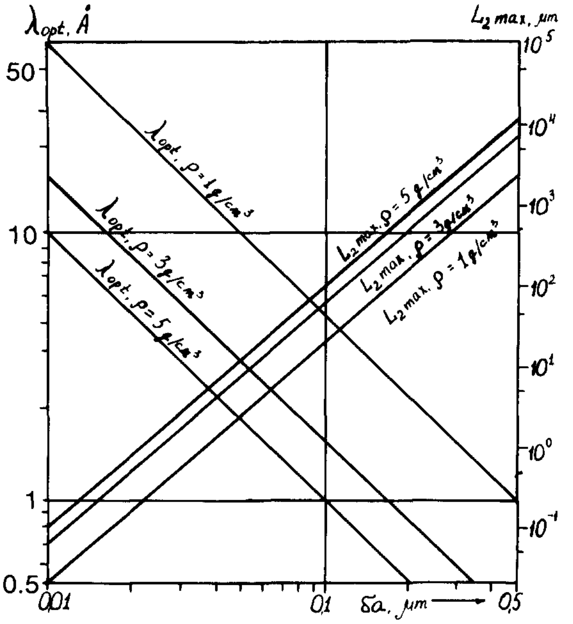

Fig. 8. The dependence of the optimal wavelength (λ_{opt}) and of the gap between X-ray mask and wafer ($L_{2\max}$) versus resolution.

Table 2
Parameters of existing and planned X-ray sources

Type of source	Spectrum	Source spot size (cm^2)	Mean brightness (photons/cm^{2}s)	Mode of operation
X-ray tube, Si-target P = 25 kW [6]	characteristic radiation $\lambda = 7.13$ Å	0.28	2×10^{16}	continuous
High-current discharge through a capillary [7]	characteristic lines of hydrogen, hydrogen-like and helium-like ions of a capillary	0.08	$(10^{12}-10^{13}) f_{\text{repeat}}$	pulse $\tau = 20$ ns
Surface spark discharge in a capillary and with electron beam [8]	-"-	2.5×10^{-5}	3×10^{17}	pulse $\tau = 120$ ns
Blasting wires [9]	characteristic radiation of wire material	4	$2 \times 10^{16} \cdot f_{\text{repeat}}$	pulse $\tau = 60$ ns
Laser plasma (100 J in the pulse of 1 ns duration) [10]	characteristic lines of hydrogen-like and helium-like ions of target	2×10^{-4}	$10^{20} \cdot f_{\text{repeat}}$	pulse $\tau = 1$ ns
Synchrotron radiation ($E = 1.5$ GeV, $I = 0.5$ A)	3–20 Å	10^{-3}	2×10^{25}	continuous
Lithographic wiggler	3–20 Å	10^{-3}	10^{26}	continuous

fact that the X-ray mask and the wafer with resist are both nonplanar $\delta a = \delta L_2 \cdot A/2L_1$ (see notation in fig. 7), one obtaines the minimum value for L_1:

$$L_{1\min}^2 = \frac{(\Delta \cdot L_2)^2 + (\delta L_2 \cdot A/2)^2}{\delta a^2}. \qquad (5)$$

Here L_2 cannot be equal to zero because the thickness of the resist and that of the absorbing layer in the X-ray mask contribute (even in the scheme of contact lithography with ideal flatness). Using eq. (5), one obtains the expression which establishes a relationship between exposure time, source brightness and admissible resolution:

$$t = \frac{\bar{n}d}{\eta(1 - e^{-\mu d}) B \delta a^5} \left[L_2^2 + \left(\frac{\delta L_2 \cdot A}{2\Delta} \right)^2 \right]. \qquad (6)$$

This expression is convenient to use for comparing the throughput of lithographic systems using different sources because the choice of all the parameters, besides B and Δ, is due to technological requirements common for different systems.

The parameters of various types of X-ray sources, which are being used or designed, are presented in table 2.

As is seen from table 2, SR and lithographic wigglers have the highest brightness. The brightness will play a particular role for replication of structures with submicron elements with a sufficient throughput. It follows from expression (6) that with optimization of the parameters of a lithographic system such as L_2, A, $\bar{n}$, d, which are determined by technological requirements, further decrease in the size of the resolved element δa is possible only due to a sharp increase in brightness ($B \sim 1/\delta a^5$). In connection with this, it seems that synchrotron radiation generated by storage rings and by special devices on the basis of storage rings are promising as the sources for X-ray lithography.

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