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COMPUTER SIMULATION OF RESIST HEATING IN ELECTRON-BEAM LITHOGRAPHY

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A computer program TEMP has been developed to simulate resist heating in electron beam lithography. Comprehensive simulations have been carried out to compare the resist-heating effects for Gaussian-beam scanning exposure and shaped-beam exposure. Temperature rises for low and high sensitivity resist on a silicon or on a quartz substrate, and on a quartz substrate with and without a chromium layer between resist and substrate have been studied.

1. INTRODUCTION

Thermal effects in resist have become more important with the development of high throughput electron beam lithography systems [1-3]. The large amount of energy deposited in resist during electron beam exposure can cause a significant temperature rise, which can result in the local enhancement of resist sensitivity [4]. Pattern distortion and nonuniformly developed resist images, caused by resist heating, have been observed experimentally for substrates with low thermal conductivity such as glass mask plates [5]. Due to the difficulty of direct measurement of temperature rise in resist, theoretical models have been proposed to calculate the resist heating effects [6-8].

These theoretical approches depend on an analytical description of electron energy deposition, which is not valid for composite materials such as a resist layer on top of a substrate. Further, only the distribution with depth is treated, and not the lateral distribution.

A computer program, TEMP (Thermal Effects Modelling Program), has been developed to determine quantitatively the extent of the resist heating effects. The 3-D Monte Carlo method has been used to simulate the electron energy deposition in different materials, and a 3-D finite difference method is used to calculate the time-dependent temperature distributions in resist and substrate. Comprehensive simulations have been carried out to compare resist heating for Gaussian-beam scanning exposure and shaped-beam exposure. Temperature rises for low and high sensitivity resist on a silicon substrate or on a quartz substrate, and quartz substrate with and without a chromium layer between resist and substrate have been studied.

2. NUMERICAL MODELLING

To calculate accurately the temperature rise in resist, the electron energy deposited in resist and substrate must be simulated accurately. Although a polynomial can be derived to fit Monte Carlo simulation results [9], it is one-dimensional, being a function of depth only, and is valid only for a single material, either resist or substrate. For a system of resist and substrate, the energy deposition in depth is discontinuous at the interface between resist and substrate. Backscattering of electrons increases with increase of substrate density, changing the electron energy deposition in the resist. Such features cannot be represented analytically. Therefore the direct use of Monte Carlo simulation results gives a more accurate estimation of heat production by electron beam irradiation.

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The TEMP software is based entirely on a numerical approach. It consists of two parts: 3-D Monte Carlo simulation and 3-D thermal simulation. The materials to be exposed are divided into a large number of cubic cells. Electron energy is accumulated in the cells along the path where electrons pass through. Energy deposition data is then transferred to the 3-D thermal simulation programs. The finite difference method used in the programs uses the 3-D finite difference cells which are naturally matched with the cubic cell used in the Monte Carlo calculation. TEMP is written in FORTRAN, and currently runs on a VAX-3100 computer. A special double-cell scheme has been developed to reduce the requirement on computer memory. TEMP is capable of simulating Gaussian beam scanning exposure or shaped beam exposure for single materials or multi-layer materials; with input data of electron beam parameters, material types, pattern size and scanning sequence, the output result is the time-dependent temperature distribution in three dimensions.

3. SIMULATION RESULTS

Simulations have been carried out with TEMP for shaped-beam flash exposure and Gaussian-beam scanning exposure. Generally, the resist temperature increases with increasing electron-beam size, beam current density and exposure dose. Figure 1 shows temperature rises for a 2 µs shaped-beam exposure at 20kV, with 20µC/cm^2 and different shaped-beam sizes, and Fig. 2 shows the temperature rises for a 1×1µm shaped beam at 20kV and 20µC/cm^2 with different beam current densities, resulting in different exposure times. Although at low beam voltage a larger fraction of the electron energy deposits in the resist layer, the initial rate of rise of resist temperature is not strongly dependent on beam voltage because higher voltages necessitate correspondingly higher exposure doses.

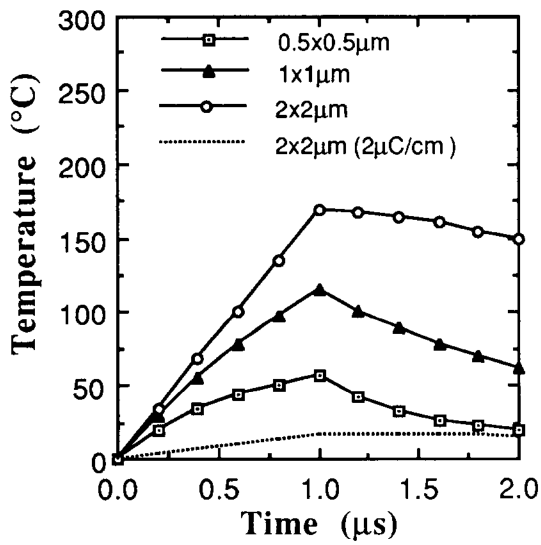

Fig. 1 Temperature rises at resist surface with different shaped-beam sizes

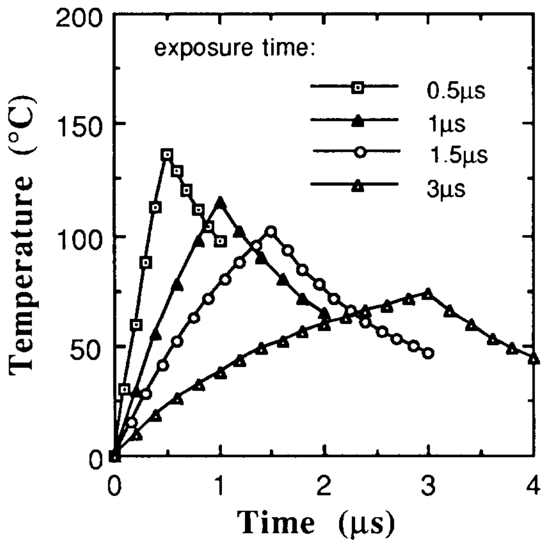

Fig. 2 Temperature rises at resist surface with different exposure times

Irradiation with larger cross-section electron beams produces more heat not only in resist but also in substrate, and the thermal conductivity of substrate strongly affects the resist heating. For a low-conductivity quartz substrate, the temperature rise in the substrate can be higher than in the esist for a very large beam size, Fig. 3. Even after the exposure is finished, the resist temperature continues to rise due to heat conduction outwards from the substrate. This effect is not found for silicon substrates, as their thermal conductivity is a hundred times higher than that of quartz. In optical mask plates there is a chromium layer between resist and quartz substrate. Although chromium has much higher thermal conductivity than quartz, it does not help to reduce the resist temperature; much more energy is deposited in the chromium layer because of its higher density, and this results in even higher temperature rise in the resist, Fig. 4.

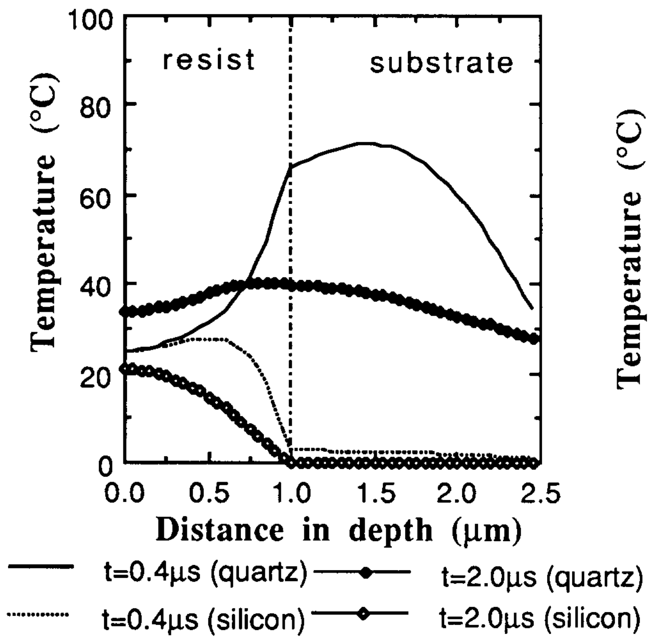

Fig. 3 *Temperature distributions in depth with quartz and silicon substrates for a 10x10μm shaped beam exposure at 20kV, for the same total dose of 2μC/cm², and 0.4μs exposure time*

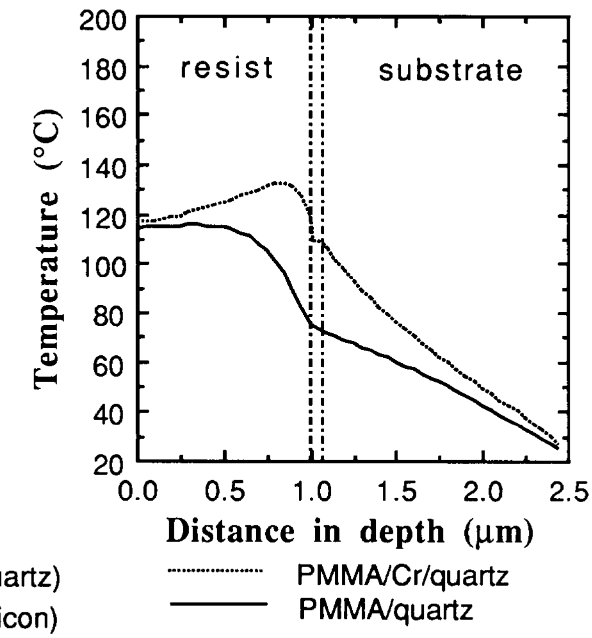

Fig. 4 *Temperature distributions in resist and in quartz substrate with and without chromium layer (0.1μm thick) in between, for a 1x1μm shaped beam at 20kV, 20μC/cm² and 1μs exposure time*

Because of the slow dissipation of heat through resist and quartz substrate, the heat produced by previous exposures in a scanning electron beam lithography persists. After an electron beam is scanned over a pattern, the whole pattern area will be heated. Figure 5 shows the difference between the temperature contours for the first pixel and for the last pixel. Compared with the scanning beam exposure, the shaped beam exposure deposits electron energy in a much short time if the same size of pattern is exposed and same current density is used. Therefore much higher temperature rise in resist is expected as in Fig. 6.

4. CONCLUSIONS

A new computer program TEMP has been developed to simulate resist heating in electron beam lithography. Monte Carlo simulation of electron energy deposition has been used directly to calculate the 3-D time-dependent temperature distributions in resist and substrate. The simulation results have shown that apart from the electron beam parameters, such as beam size, beam current density and exposure dose, the thermal conductivity of substrate has a strong effect on the resist heating. This confirms the fact that the thermal effects of resist so far has only been found on optical mask plates [10]. The use of high-sensitivity resist would reduce the thermal effects significantly.

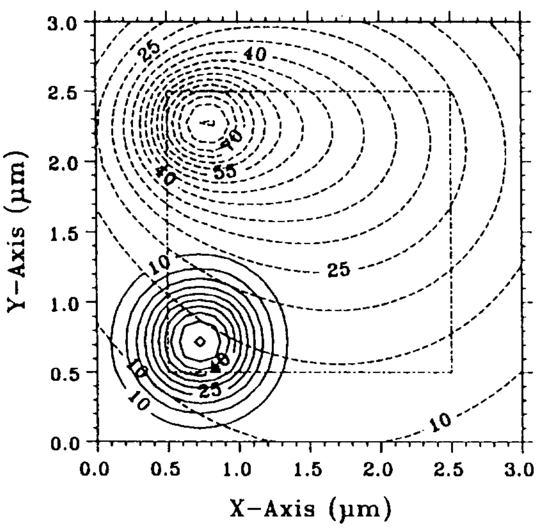

Fig. 5 Temperature contours of the first pixel (solid line) and the last pixel (dashed line) for a Gaussian beam scanned a 2x2μm square at 20kV, 20A/cm^2 and 20μC/cm^2 (the central frame is the exposure area).

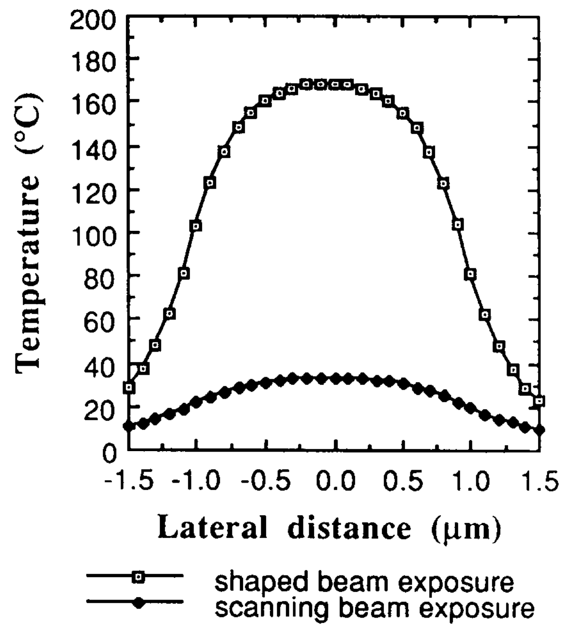

Fig. 6 Temperature distribution at resist surface for a 2x2μm shaped beam and time-averaged temperature distribution for a Gaussian beam scanned over the 2x2μm square at 20kV, 20A/cm^2 and 20μC/cm^2

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