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Development of an e-beam lithography process for PMMA resist

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Electron beam lithography is a very popular technique to produce structures with submicrometric dimensions, specially for studying advanced devices like $GaAs$ based FETs or quantum devices. A scanning electron microscope (SEM) was adapted for this purpose. Our first attempts to produce such devices exploring the high resolution capabilities of the SEM were successful. Exposures for design with high level of integration should present problems like proximity effects, that arises from the electrons backscattered from the resist/semiconductor interface. Corrections to this kind of problem is done through a numerical simulation of the electron-matter interaction process (a Monte Carlo-like simulation). This kind of simulation anticipates the energy density distribution profile dissipated through the resist and corrects it to get a profile that fits to the best development results. These simulations were used to develop a lift-off process with a bilayer PMMA resist (two different molecular weight) obtained in house.

I. INTRODUCTION

Electron beam lithography is an established tool for the modern microelectronics prototyping and research. Its high resolution capability is the main feature that has attracted major interest on it. Although it has some drawbacks, like the low throughput, it suits well for research purposes. Structures as small as 50 nm can be fabricated with this technique [1,2]. One very popular approach to produce this very small structures is the lift-off process [3]. This process consist in transferring a pattern to a resist layer followed by a metal deposition as depicted on figure 1. The resist has a very particular profile after it's development: there's a protuberance at the border of the top layer. This protuberance protects the area near the wall from metal deposition, creating a discontinuity on the deposited metal layer. After the deposition, the resist layer is stripped from the wafer surface, together with the metal on the top of the resist, leaving behind just the metal deposited directly on the top of the semiconductor substrate.

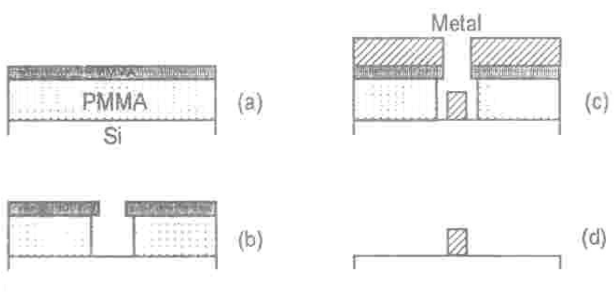

FIG. 1. A lift-off process. Two layer resists are cast on the wafer (a), followed by exposure and development (b), metalization (c) and the lift-off (d).

At this work, we'll show a lift-off process that we have developed to fabricate gates for $GaAs$ based transistors. In general such devices can be made with standard techniques (i.e. optical lithography), except by the transistor's gate, that normally is defined by a high resolution technique like e-beam lithography (in general it has dimensions with less than 0.5 μm).

A computer program for process simulation was applied to find the best condition to "write" the structures on a silicon wafer. The interaction between the electrons from the beam and the resist is a very complex process. High energy electrons interacting with matter generates a variety of reactions. Together with the secondary electrons that are generated from the excitation of the atoms, there are Auger electrons, photons and backscattered electrons. This last one and the secondary electrons are the most important for the lithographic process. A simulation of this process of interaction can be performed by a Monte Carlo algorithm and the analysis of the energy dissipated by the secondary and backscattered electrons through the resist layer helps to predict the result of a lithographic process. A commercial program, CASINO from Cambridge/Leica [4], was used to perform these simulations. It applies the Bethe electron deceleration relation and the Rutherford cross section with shielding to calculate the energy dissipation [5]. An important limitation of this simulator arises from its cross section algorithm, so that for energies below 10 keV and for massive atoms like gold, it doesn't predict the right energy dissipation. For a best calculation, we need a full calculation of the cross section, which is very time demanding. An implementation of this kind of simulation will be reserved for purpose the future, when we'll focus our attention on low energy lithography. For the purpose of this article, this simulator that is for electrons 20 keV energy and a target of PMMA on silicon, it works very well. The energy dissipated in the resist layer can be related with the dissolution rate of the exposed resist under development in methylisobutylketone:isopropil alcohol (MIBK:IPA), 1:3, developer. In this way, a contrast curve was constructed for each resist , and each dose was related with a dissipated medium energy density, that was obtained from the simulator. Figure 2 summarizes this approach. With these information we can predict the profile of the exposed resist after the development and before real exposure.

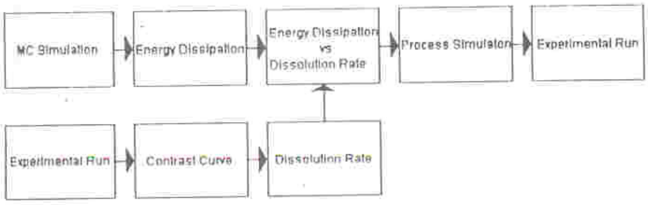

FIG. 2. Summary of our procedures to compare the simulations with experiments.

II. EXPERIMENT

The e-beam resist used in this work was prepared in house following a standard recipe from the literature [6-8,10]. Two industrial grade PMMA, from ICI, ELVACITE 2008 and 2041, were dissolved with MIBK and then applied with a spin coater on a clean silicon wafer surface. The thicknesses were approximately 0.75 μm and 0.25 μm, respectively. After casting, the resist was baked for at least 45 minutes at 175°C. The two resists were applied on the silicon wafer, with the ELVACITE 2008 working as the bottom layer and the ELVACITE 2041 working as the top layer. This bilayer process is known to produce a mushroom like profile for lift-off. For the bilayer process, after each casting of the resist, the baking was repeated. These resists are brands of PMMA with different molecular weights (25,000 and 350,000 respectively), which will reflect in different dissolution rates. The ELVACITE 2041 top layer on ELVACITE 2008 bottom layer, it will create the desired profile for lift-off after development. The exposure was performed on a Philips 515 SEM, modified to work as an e-beam writer with a Proxy-Writer lithographic system from Raith [9]. The beam spot size was mantained fixed on approximately 400 nm for all exposures and the beam current was monitored with a picoammeter (Keythley model 485). Several 500 μm long and 20 μm width lines had their depth measured after development with a Dektak 3030 step-height meter. This enable us to get the contrast curves for the process simulator. After the simulations, optimizations, a 2 mm long and 0.5 μm wide lines were fabricated to analyse the results. To produce the SEM photographs of the samples, they were coated with a thin layer of gold to avoid charging.

III. DISCUSSION

The PMMA polymer suffer a process of chain scissoning when exposed to radiations like U.V. or x-ray. High energy electron cans produce the same effect on the polymer, although the process of exposure is a little bit different. This e-beam exposure in a reduction of the molecular weight of the polymer, that reflects on it's solubility. On this bilayer configuration, the top resist layer should dissolve slower than the lower resist layer, and this will guarantee the necessary profile for lift-off.

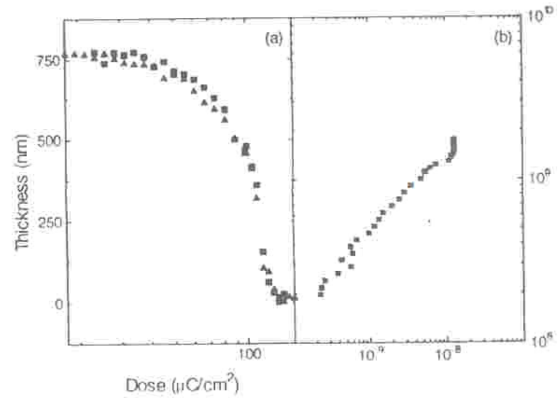

FIG. 3. (a) Contrast curve for a PMMA resist (ELVACITE 2008) with 0.75 μm thickness (triangles and squares are for the same sample, but different measurement), and (b) after the conversion to a dissolution rate versus the dissipated medium energy density.

Figure 3(a) shows the contrast curve for the PMMA resist ELVACITE 2008. For 0.75 μm thickness, it is necessary a dose of 130 $\mu C/cm^2$ to remove all resist (the so called clearing dose). Another important parameter to evaluate the process is the resist contrast, γ. Although its reported values are in the 1.8-7.8 range, this variation is mainly caused by the accuracy of measurement [10]. From our measurings for the ELVACITE 2008 we found a value for γ of 2.0. For the ELVACITE 2041 resist the clearing dose was approximately of 210 $\mu C/cm^2$ and γ was 2.7. At low doses we can see that there is a great uncertainty for the removed thickness. This is caused by striations on the surface of the resist after the casting, and this creates a variation on the thickness of more or less 35 nm. This variation reflects on the measurement of the removed thickness. The PMMA resist ELVACITE 2041 didn't show this striation and the contrast curve was cleaner than the other resist. With the simulation we could extract the dissipated medium energy density through the resist and associate this with the contrast curve. The figure 3(b) shows this conversion. The conversion is simply performed simulating the medium value of the energy dissipation on similar exposure conditions. With this data, the next step is to simulate bilayer process, the figure 4 shows a simulated exposed resist cross section after development for several doses. The development condition was fixed (development time of 60 s at 25°C), followed by a rinse on IPA and dry blew with nitrogen). Good control of the development temperature is important because it is known that it has great influence on development [7]. The beam spot size of the simulation was fixed on approximately 400 nm. The size of the beam spot size was estimated through the SEM calibration procedure.

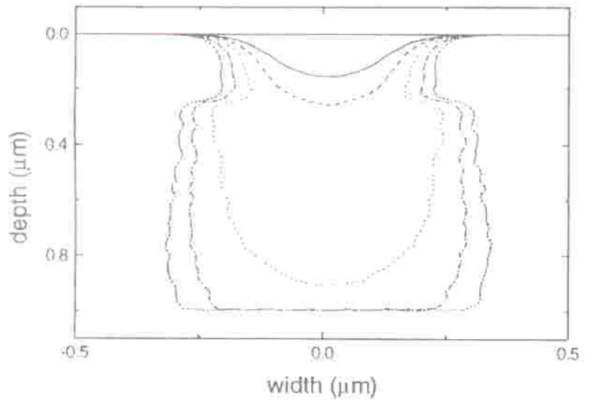

FIG. 4. Simulation for a development of a bilayer resist on silicon for several doses (CASINO simulator), for doses from 125 through 225 $\mu C/cm^2$ with dose steps of 25 $\mu C/cm^2$.

After the simulation several lines were exposed for different doses. The best results were obtained for a dose of 200 $\mu C/cm^2$. The lines were 2 mm long, but we didn't find any significant distortion on the line by SEM inspection. This indicates that the SEM has capabilities to write quite long lines in a very flat way. Figure 5 shows a SEM picture of a sample after development. It shows a good agreement with the simulation. The typical profile for lift-off can be seen. The width of the top layer is near 0.6 μm. Some proximity effects can be seen on the picture since the center gaps are larger than the gaps in the edge. A full simulation of whole the structure should be useful to predict and correct this effects. For structures like equal spaced parallel lines this corrections are simple and can be done by a trial and error method, but for complex structures this kind of correction is very difficult. For this kind of problem a simulation can be extremely useful.

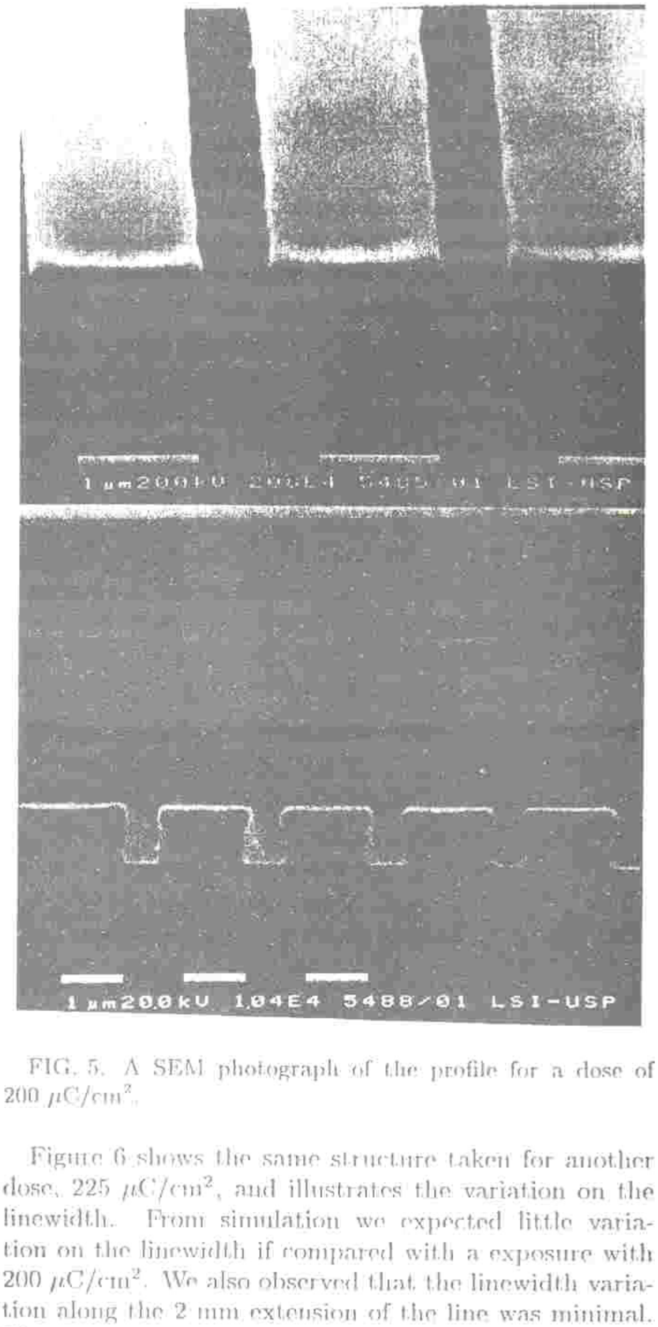

FIG. 5. A SEM photograph of the profile for a dose of 200 $\mu C/cm^2$.

Figure 6 shows the same structure taken for another dose, 225 $\mu C/cm^2$, and illustrates the variation on the linewidth. From simulation we expected little variation on the linewidth if compared with a exposure with 200 $\mu C/cm^2$. We also observed that the linewidth variation along the 2 mm extension of the line was minimal. This regularity with the linewidth through such a extend lines is important for devices like HEMT transistors.

For real devices it is desired to have a smaller dimension on the linewidth. This can be achieved with optimization of both simulation and process. This efforts are under way through an experimental design approach. This approach should produce the best conditions for the process under minimum beam spot size.

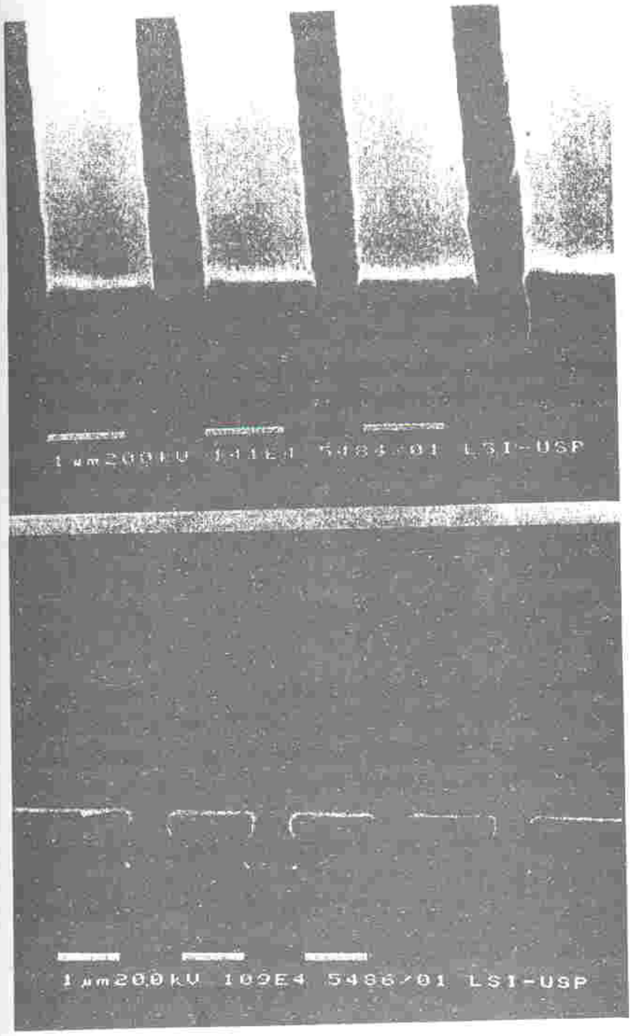

FIG. 6. A SEM picture for lines written with a dose of $225\mu C/cm^2$.

IV. CONCLUSION

PMMA resist exhibit a high clearing dose (more than $100\ \mu C/cm^2$) if compared with commercial e-beam resists (under $50\ \mu C/cm^2$), but it exhibits high resolution capabilities too. Resists based on industrial grade PMMA can be used to fabricate structures with submicrometric dimensions. This should be an advantage, since ready use PMMA resists are expensive. We have successfully written lines with submicrometrics dimensions without difficult. The striation that arises on this kind of resist (ELVACITE 2008) can be reduced a different kind of solvent [11]. For a process with a resist layer as thick as we had, the striations are not a serious problem. The simulator was useful to predict the condition for the correct exposure and even to calculate the proximity corrections. Although this kind of simulation was not very useful for this kind of application, parallel lines, it can solve the problem for complex patterns.

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[1] B. Houli, V. Umansky, and M. Heiblum, Semicond. Sci. Technol., **8**, 1490 (1993).

[2] H. Yamashita, and Y. Todokoro, Electron. Lett., **21**, 645 (1985).

[3] W. M. Moreau, *Semiconductor Lithography* (Plenum Press, New York, 1991), p. 581.

[4] Leica Cambridge Ltd, Clifton Road, Cambridge CB1 3QH, UK.

[5] K. A. Valiev, *The Physics of Submicron Lithography* (Plenum Press, New York, 1992).

[6] I. Haller, M. Hatzakis, and R. Srinivasan, IBM J. Res. Develop., **12**, 251 (1968).

[7] J. S. Greeneich, J. Electrochem. Soc., **122**, 970 (1975).

[8] H. Ryssel, K. Haberger, and H. Kranz, J. Vac. Sci. Technol., **19**, 1358 (1981).

[9] Raith GmbH, Hauert 18 (Technologiepark), D-44227 Dortmund, Germany.

[10] K. Harada, T. Tamamura, and O. Kogure, J. Electrochem. Soc., **129**, 2576 (1982).

[11] W. M. Moreau, *Semiconductor Lithography* (Plenum Press, New York, 1991), p. 296.