High-Resolution Electron-Beam Lithography and Its Application to MOS Devices

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A point electron-beam lithography system using a thermal field emitter (TFE) allows us to use a nanometer-level fine electron beam to investigate nano-fabrication techniques and minute devices. We developed an organic negative resist, called calixarene, which has low molecular weight of 972 and almost monodispersity. This resist shows a high resolution of about 10 nm when it is exposed to an electron-beam system of 50 kV using TFE. The newly developed resist has been applied in order to fabricate an EJ-MOSFET (electrically variable shallow junction metal-oxide-semiconductor field effect transistor). A 14-nm-gate-length EJ-MOSFET was fabricated by using a calixarene resist and an electron-beam exposure system, and showed MOS device performance.

1. Introduction

For the past 30 years, the packing density of LSIs (Large Scale Integration) has been increasing and by using optical lithography such as i-line and KrF excimer laser stepper, a minimum feature size of 0.18 μm is under production. The performance of devices such as clock speed and consumption power can be improved by reducing its feature size. Regarding the future MOS LSIs, devices with a minimum feature size of less than 0.1 μm will be investigated because the feasibility and performance of such MOS devices with small gate lengths are unclear [1]. Yet at moment, a lithography system for mass production is not available for sub-0.1 μm. Therefore, Gaussian or point electron-beam lithography system is the only tool used for the deep sub 0.1 μm region [2-4]. The resolution of a lithographic pattern is not only governed by the resolution of the lithographic tool itself but also by the resolution of the resist. In this report, the development of a high-resolution resist for nanolithography and its application of minute MOS device fabrication is presented.

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2. High-resolution resist; calixarene

PMMA is a well-known high-resolution positive resist that has been used for nanofabrication and for testing the feasibility of electron beam lithography machines [5]. When using electron beam lithography to reduce an exposed area so that a high throughput is obtained, a negative tone resist is useful, especially for the gate patterning in MOS devices.

We have investigated a mechanism for resist resolution and have developed a new type of resist, called calixarene [6]. We found that the resolution of an organic negative resist depends on the molecular size of its composed material of resist by using polystyrene resist [7]. The average molecular weight of a negative tone resist ranges from several thousands to several ten thousands and its molecular size or diameter ranges from a few nanometers to several tens nanometers. These resists show a resolution of only a few tens nm [8]. It is important to obtain low molecular weight resin of about 1000 or less for the high resolution. The roughness of the resist pattern is affected not only by the molecular size of the resist but also by dispersion [9]. Calixarene used in this experiment has a low molecular weight of about 1000 and almost monodispersity. The diameter of the molecule is about 1 nm.

Calixarene[10], which is a general term for specific cyclic phenol resins, is a cyclic oligomer. The calixarene resists used in this experiment consist of 6-phenol and have a molecular diameter of 1nm [11]. The molecule shown in **Fig.1 (a)** is a calixarene derivative, hexaacetate *p*-methylcalix[6]arene (MC6AOAc) that has a molecular weight of 972, while the molecule shown in **Fig. 1 (b)** is a calixarene derivative, hexa-chloromethohexa-methoxycalix[6]arene (CMC6AOMe) that has a molecular weight of 996. Most calixarene derivatives have poor solubility in organic solvents, but these calixarene molecules are soluble in organic solvents such as *o*-dichlorobenzene and they have a high heat resistivity up to 590 K [12].

Therefore, films of calixarene are made easily by using a spin coating method similar to that used in conventional resist processes. We found that these calixarene films work well as negative electron-beam resists and that they show ultrahigh resolution and high durability under halide plasma etching.

The electron beam exposure characteristics of these calixarene films are shown in **Fig. 2.** The electron beam lithography system used is JBX-5FE/6000FS which are produced by JEOL Ltd [13]. By using a thermal field emitter (TFE), the beam diameter is 5 nm at an acceleration voltage of 50 kV. We spin coated 1weight % of a calixarene solution on a Si wafer at 3000 rpm for 30 s to prepare a 30-nm-thick film. For MC6AOAc, the threshold sensitivity was about 0.8 mC/cm^2 and the practical sensitivity was about 7 mC/cm^2, which is almost 20 times higher than that for PMMA and almost 100 times higher than that for a SAL601 chemically amplified negative resist. The sensitivity of the chloromethylated calixarene CMC6AOMe is about ten times higher than that of MC6AOAc. Substituting Cl atoms in the methyl groups generally improves the sensitivity because the Cl bonds easily decompose when the C-Cl bonding energy is low. Activated Cl can affect Cl bonds at other sites and it can reduce their bonding energy. Their Cl bonds can then be broken by a low energy deposition. The resist contrast γ is about 1.6 for each calixarene resist.

Line and dot patterns using a calixarene resist are shown in **Fig. 3** and **Fig. 4.** The resist line pattern was made on a thin Ge film deposited on a silicon wafer. The resist dot pattern was made on a silicon wafer. Both line width and dot diameter are 15 nm. By using SAL601 which is a chemically amplified negative resist, we achieved a minimum line width of 30 nm. Therefore, calixarene resist provides us with very fine line and dot patterns.

3. Fabrication of 14-nm EJ-MOS devices

To fabricate a small gate length MOSFET, such as sub-0.1 μm, suppression of short-channel effects is important. To avoid any problems, it is necessary to make a shallow junction for the source and drain region. In this experiment, we propose an electrically variable shallow junction metal oxide semiconductor field effect transistor (EJ-MOSFET) [14, 15]. **Figure 5** is a schematic cross section of an EJ-MOSFET. Shallow junctions are usually made by thermal doping or ion implantation, but

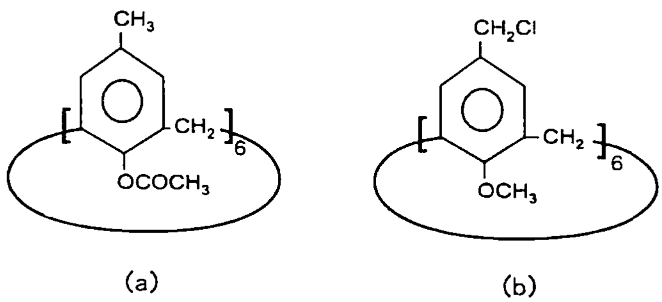


Fig.1. Chemical structure of calixarene: (a) MC6AOAc, (b) CMC6AOMe. The molecular weights are (a) 972 and (b) 996, respectively. The molecular size is about 1 nm.

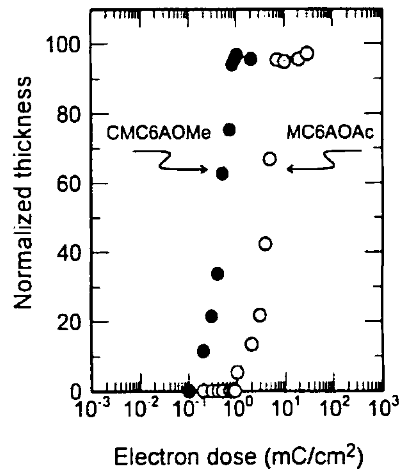


Fig.2. The exposure characteristics of calixarenes. The electron beam used is 50 kV and the diameter of the point beam is 5 nm.

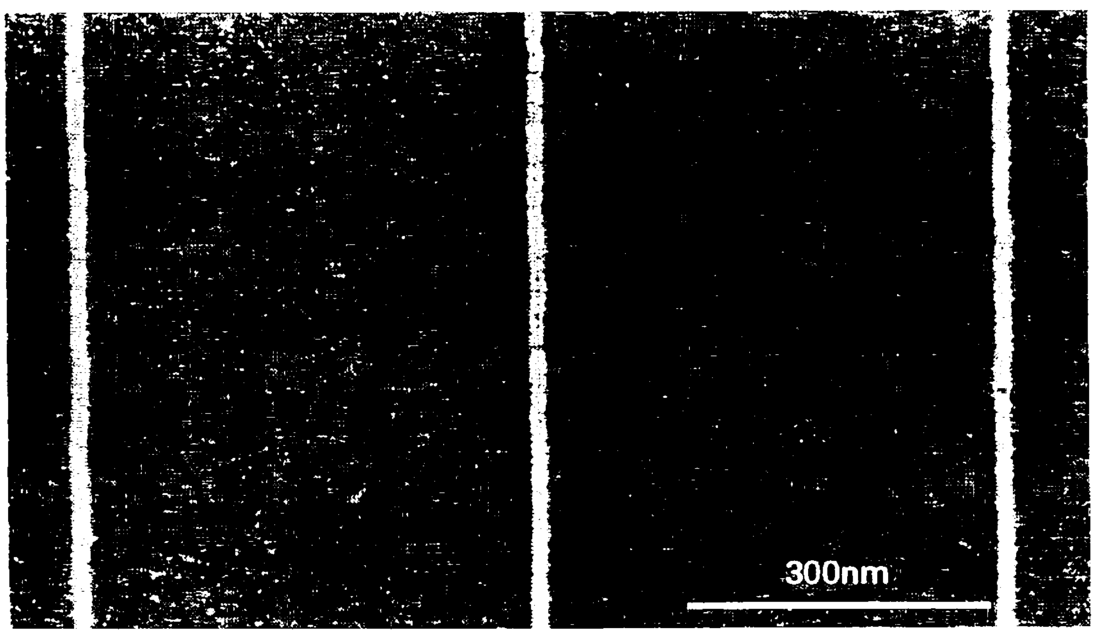
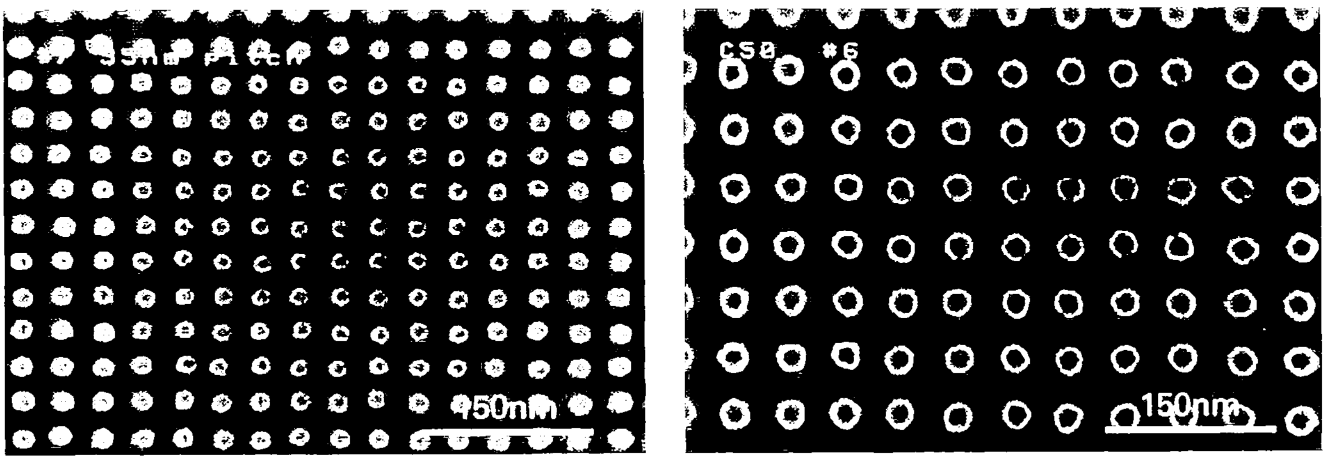


Fig.3. Line pattern made by calixarene, MC6AOAC, on a Ge film deposited on a silicon wafer. The electron doses is 60 nC/cm.

with regard to the EJ-MOSFET, the shallow junction is made by using an electrically induced inversion layer. The gate oxide thickness is 5 nm which is grown through thermal oxidation. The 40-nm-thick poly-Si lower gate (this is an ordinary gate) is defined by EB-direct writing onto a calixarene resist and by dry etching with CF_4 gas. The other part is defined by optical lithography. The poly-Si gate is covered by a 20-nm thick intergate oxide made by chemical vapor deposition (CVD) and the Al/Au upper gate is deposited by thermal evaporation. This upper gate induced an inversion layer which acts as a shallow junction. The junction depth is about 4.5 nm. **Figure** 6 shows a cross sectional transmission electron microscope (TEM) image of a fabricated EJ-MOSFET, whict has a poly-Si gate length of 14-nm embedded in the gate oxide and intergate oxide [16]. **Figure 7** shows the drain current versus the drain voltage as a function of the gate voltage for EJ-MOSFET at 300 K. The gate width is 10 μm. A short channel effect gradually occurs under a gate length of 30 nm and there is no saturation characteristics of drain current in the 14-nm gate EJ-MOSFET. However, the drain current is modulated by changing the gate voltage, which means that MOSFET with a short gate length, such as 14-nm, could perform if the short channel effect is suppressed using, for example, a thin gate oxide, a highly doped substrate, and a shallow junction.

4. Newly developed 100-kV electron beam system

The size of silicon wafers increases with increasing chip size and device density so that high productivity is obtained and production cost is reduced. Currently, 8-inch wafers are used in both R&D and mass production, but in the near future, 12-inch wafers will be introduced to the semiconductor industry. As we have already mentioned, research in sub-0.1 μm device continues intensively. In order to obtain



(a) MC6AOAc d = 15nm, period = 35nm, t = 40nm (b) CMC6AOMe d = 25nm, period = 50nm, t = 40nm

Fig.4. Dot pattern made by calixarene. The electron dose is 1×10^5 electrons/dot.

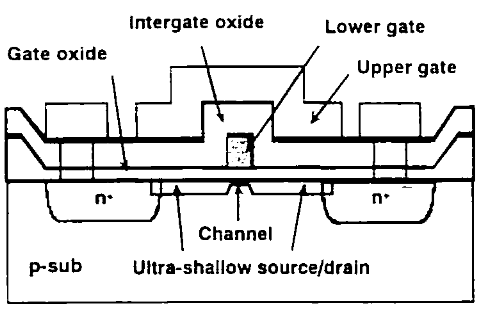


Fig.5. Cross sectional device structure of an EJ-MOSFET. The calixarene resist is used to delineate a polysilicon gate.

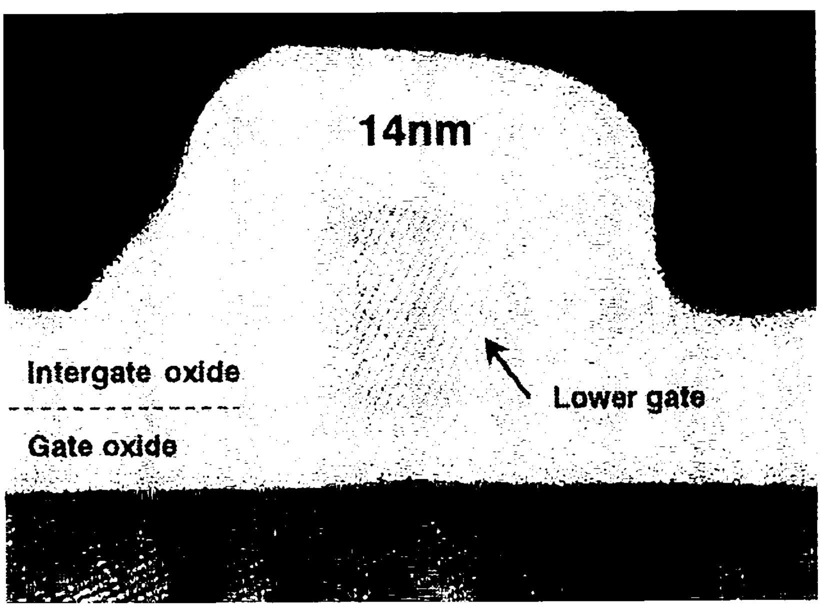


Fig.6. Cross sectional TEM image of an EJ-MOSFET. The 14-nm-polysilicon gate is well defined by using calixarene and dry etching.

high throughput, chemically amplified resists are commonly used in both optical and electron beam lithography. Therefore, a high-resolution electron-beam lithography system requires a chemically amplified resist and large wafers for next generation process. Recently, a new point electron-beam system, known as JBX-9300FS, has been developed (**Fig. 8**) [17]. This system has an acceleration voltage of 100 kV which allows high resolution and high aspect ratio lithography for a large deflection field. The minimum beam diameter of less than 4 nm is obtained at 500 μm field, at a beam current of 100pA, and an acceleration voltage of 100 kV. The maximum deflection clock is over 25 MHz. An 8-inch wafer is available for full exposure and a 12-inch wafer is loadable. The system has an automatic wafer cassette loader which can be used with an automatic coater and developer. This system is useful for the research of high-performance Si-MOS devices and LSIs.

5. Summary

High-resolution nanolithography using a newly developed electron-beam resist, called calixarene, and its application to device fabrication have been shown. We found that a calixarene negative resist has a high-resolution of 10 nm when it is combined with a 50-kV point electron-beam lithography system using TFE. The resist has a low molecular weight of about 1000 and a molecular diameter of 1 nm. This negative resist almost has the highest resolution when it is compared with other negative resists reported elsewhere. By using this resist, we developed a 14-nm-gate length EJ-MOSFET for gate patterning and showed MOS device performance. This device has the minimum gate length on a silicon wafer. The high resolution resist and point electron beam-lithography system allows us to use nano-fabrication techniques in a conventional device process.

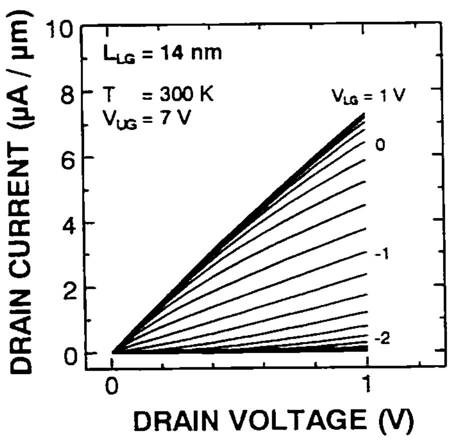


Fig.7. Drain current vs drain voltage (I_D-V_D) characteristics of EJ-MOSFET with a lower gate length (L_{LG}) of 14 nm at room temperature. The upper gate voltage (V_{UG}) was fixed at 7 V and the lower gate voltage (V_{LG}) was biased from -3 to 1 V in 0.2 V steps.

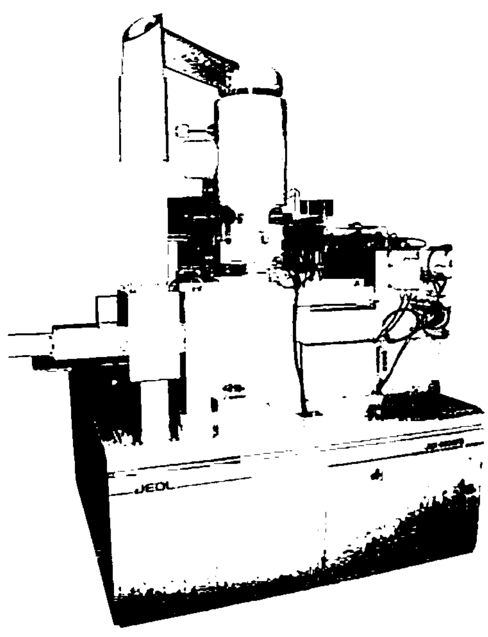


Fig.8. Photograph of a newly developed 100-kV electron-beam lithography system, JBX-9300FS.

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