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Pattern transfer fidelity of nanoimprint lithography on six-inch wafers

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Abstract
We studied the pattern transfer fidelity of nanoimprint lithography (NIL) by patterning sub-micron MESFET gates on six-inch wafers. The critical dimensions (CD) of the gate patterns on the mould, imprinted in resist, as well as after oxygen reactive ion etching (RIE) and metal lift-off were measured, separately, using an ultrahigh-resolution scanning electron microscope. Comparison of the measurements reveals that the as-imprinted gates in resist are 5.2% (or 37 nm) on average larger than those on the mould with a standard deviation of 1.2% (or 8 nm), and the gates after oxygen RIE and metal lift-off are 42% (or 296 nm) on average larger than those on the mould with a standard deviation of 8% (or 30 nm). Compared with photolithography, NIL has better pattern transfer fidelity with CD controls about four times smaller.

1. Introduction

Nanoimprint lithography [1] (NIL) is a sub-10 nm nanopatterning technology that defines patterns by mechanical deformation of a resist, followed by oxygen reactive ion etching (RIE) to remove the residual resist. Potential applications have been demonstrated in nanoelectronics [2–7], optics [8–11], high-density storage [12–14], nanomagnetic devices [15], bio-devices [16–20], transducers [21], and nanoelectromechanical elements [22]. NIL has also demonstrated multi-level alignments on four-inch wafers [23], and single-level patterning over a six-inch wafer scale [24]. Until now, the pattern transfer fidelity of NIL has not been thoroughly studied. Such information, however, is essential for using NIL in manufacturing. Here, we report our research on the pattern transfer fidelity of NIL over six-inch wafers.

2. Characterization methods

We chose to use sub-micron MESFET gates on six-inch wafers in our study of the pattern transfer fidelity of NIL. It was characterized by measuring and analysing the gates on the six-inch mould, the gates in resist imprinted by the mould, and finally the metal gates resulting from oxygen RIE of the imprinted gates in resist and lift-off of metals. The imprint procedure is shown schematically in figure 1. The gate length (or critical dimension (CD)) was measured using an ultrahigh-resolution field emission scanning electron microscope (Hitachi-S4500). In total 51 gates, which were located along reticle diagonals, were characterized, as indicated in figure 2(a).

3. Fabrication details

A six-inch mould was patterned using a 5× i-line reduction stepper, and transferred to silicon by chromium evaporation, lift-off of the chromium mask in acetone, and CHF_3/SF_6 RIE. The chromium mask was then removed in chromium etchant (CR-7). The finished mould consists of four reticles, as shown in figure 2(a). Each reticle is 1.7 cm × 1.7 cm in footprint on the wafer and consists of 210 dies. Inside each die are several gates with the average gate length of 725 nm, surrounded by large pads (figure 2(d)) with lateral dimensions from 100 to 1000 μm. The protrusion height on the mould is 800 nm, with excellent uniformity across the whole six-inch mould.

The mould was then used to imprint 1200 nm thick NP-60 (a resist made in-house) spun on a bare six-inch silicon wafer. The pressure and temperature were 600 psi and 130 °C, respectively. The mould and the imprinted wafer were

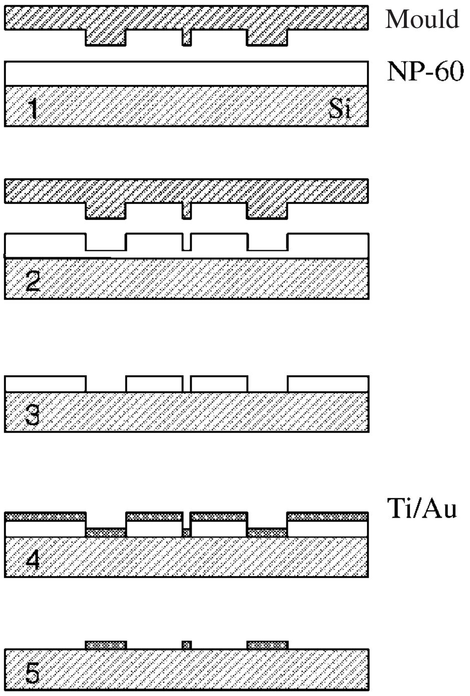

Figure 1. A schematic diagram of the NIL: (1) imprinting using a six-inch mould to deform the NP-60 resist spun on a six-inch wafer; (2) separating the mould from the imprinted wafer; (3) oxygen RIE to remove the residual NP-60 resist at the trench bottom; (4) metal deposition; (5) lift-off of metals in tetrahydrofuran.

separated manually at room temperature, and no resist peel-off occurred. Excellent uniformity was achieved in each die, as shown in figures 2(b) and (e). These resist patterns were then transferred to metals (figures 2(c) and (f)) by oxygen RIE, metal evaporation (10 nm titanium and 40 nm gold), and lift-off in tetrahydrofuran. Figures 2(g)–(i) show one gate on the silicon mould, its duplication in NP-60 resist, and the final metal pattern, respectively.

4. Results

The CD measurements of the gate patterns on the mould, in resist, and in metals (figure 3) show that a fixed increase of the gate length occurred at each fabrication step. Across the whole six-inch wafers, the as-imprinted gates in resist are 37 nm (figure 4(a)) on average larger than those on the mould with a standard deviation of 8 nm (or 1.2%). The metal gates are 296 nm (figure 4(c)) on average larger than those on the mould with a standard deviation of 30 nm (or 8%). Among the four reticles, the smallest CD increase after imprint occurs in reticle 2 and the largest in reticle 3, with an intermediate increase in reticles 1 and 4. Separation of the mould and the imprinted substrate from one location close to reticle 2 might cause this difference. After long-time oxygen RIE, the differences among reticles are not obvious if one takes the standard deviations into consideration.

Compared with photolithography, NIL is capable of providing better CD controls. As shown in figure 4(b), the relative increase of gate length upon imprint is 5.2% (±1.2%) of the average gate length on the mould. The CD control (3σ) of gates imprinted in resist is then ±26 nm over a six-inch wafer. As a comparison, the resolution and CD control (3σ) of a Nikon 5x i-line reduction stepper and Karl Suss 1x i-line aligner are 350 and ±100, 1500, and ±300 nm, respectively.

5. Discussion and conclusions

We believe that the increase of the gate length upon imprint could be caused by the non-parallel alignment of the mould

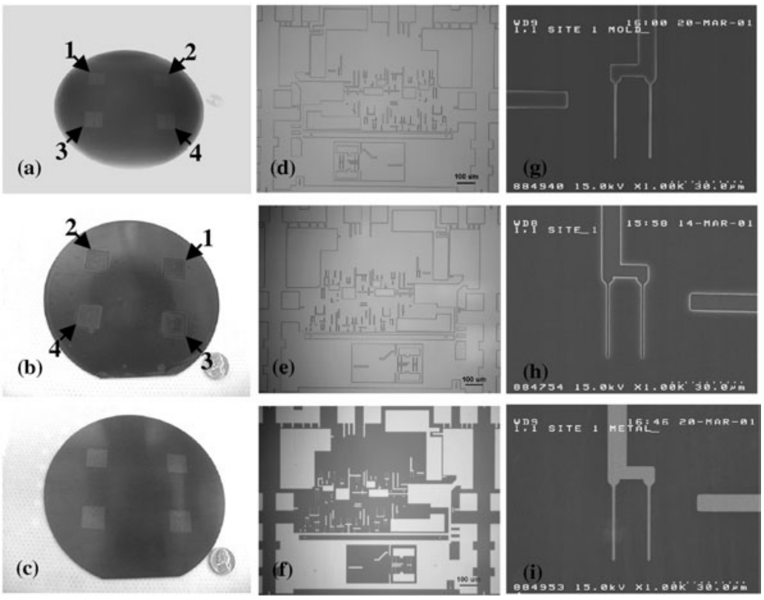

Figure 2. (a)–(c) Optical pictures of our six-inch silicon mould, resist templates, and metal patterns on six-inch silicon wafers, respectively. Four reticles were patterned on the mould. (d), (e) Optical pictures of one die on the mould, imprinted in NP-60 resist, and after metal lift-off, respectively. Excellent uniformity was obtained over the six-inch wafers. (g)–(i) Scanning electron micrographs of one gate on the mould, its duplication in NP-60 resist, and the final metal pattern, respectively.

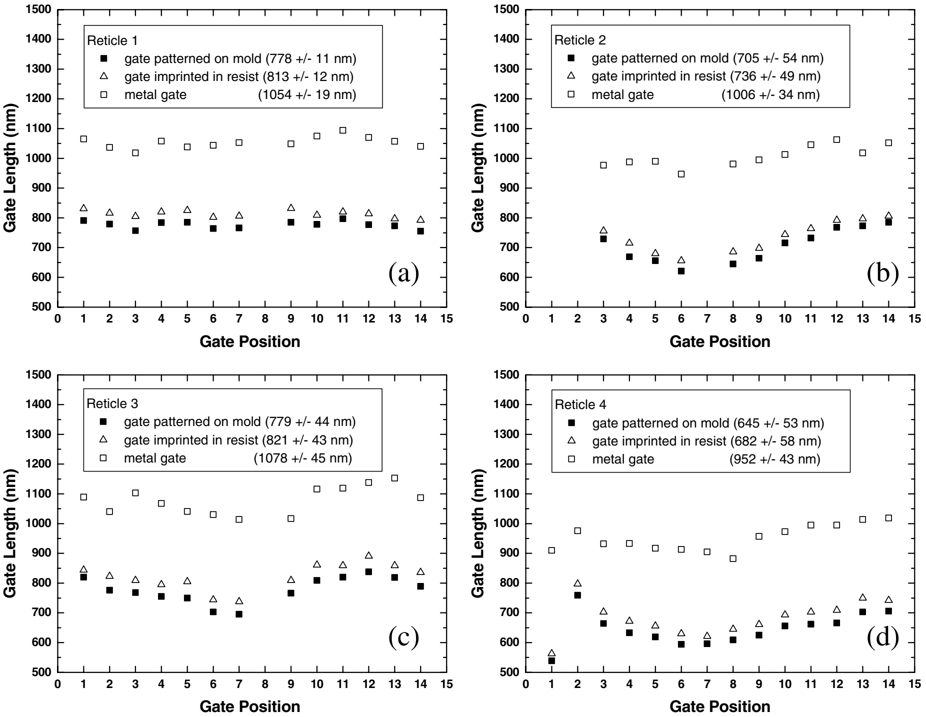

Figure 3. The CD measurements of the mould, the imprinted resist templates, and the final metal patterns in each reticle. A fixed increase in gate length was observed at each fabrication step. Dies along reticle diagonal are given numbers and these are used to label the abscissa, with no measurement being carried out in the test dies.

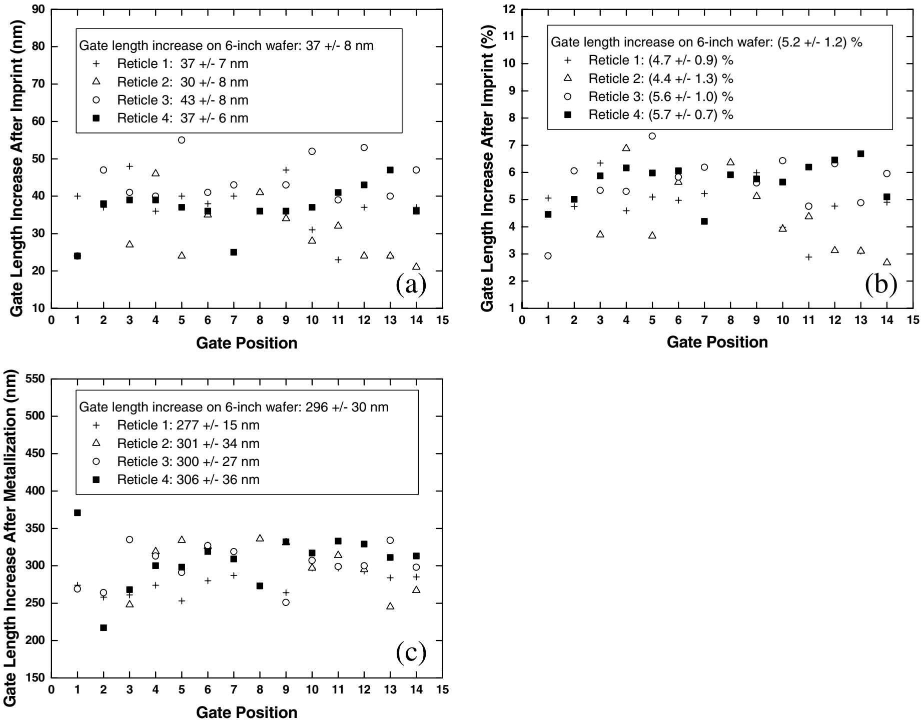

Figure 4. The increase of gate length (CD) upon imprint in four reticles is shown on scales of (a) nanometres and (b) percentages. An average CD increase of 37 nm (or 5.2%) with a standard deviation of 8 nm (or 1.2%) was obtained. (c) By comparing final metal patterns with those on the mould, an average CD increase of 296 nm with a standard deviation of 30 nm was obtained.

and substrate during separation, as shown schematically in figure 5(a). A separation tool for retaining the parallel alignment between the mould and imprinted substrate during separation is under development.

The large increase of gate length upon oxygen RIE and metal lift-off is mainly caused by the absence of an etching mask in the oxygen plasma treatment (figure 5(b)). We can estimate the thickness of the residual NP-60 resist after imprint

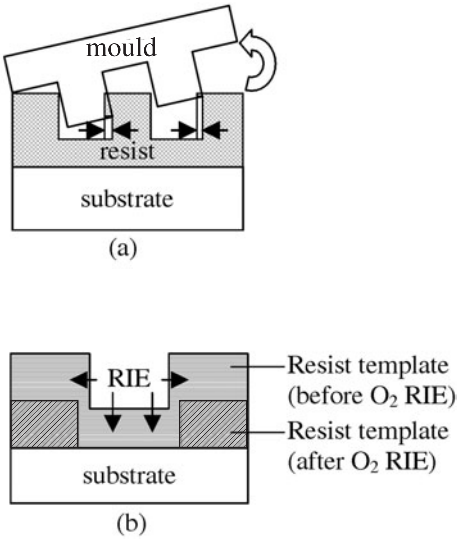

Figure 5. Two factors might cause gate length increase upon imprint: (a) separation from one corner; and (b) absence of an etching mask in the oxygen RIE.

on the basis of the resist thickness before imprinting, the resist template depth, and the pattern density on the mould. The resist on the imprinted substrate was about 1200 nm thick, and the resist templates were about 750 nm deep after imprint. The protrusions on the mould account for about 42% of the area in a die. Therefore, the residual resist at the trench bottom was estimated to be around 765 nm thick. In our experiment, we etched the imprinted substrate in oxygen plasma (50 W, 10 mTorr, 10 sccm O_2) for 34.5 min. A Dektak measurement gave the etching rate of NP-60 resist as 22 nm min^{-1}. So in total about 760 nm thickness of NP-60 resist was removed, consistent with the above estimates within experimental errors. The lateral etching rate of NP-60 was thus determined to be about 4 nm min^{-1}, on the basis of the etching time and 260 nm ($\pm$40 nm) average gate length increase during oxygen RIE. The anisotropy of the etching process is thus about 0.83.

We also studied the transfer fidelity of NIL in vertical dimensions. As inspected by a Tapping Mode atomic force microscope, the protrusion height on the mould is about 800 nm. The resist templates are about 750 nm deep for gates, and about 780 nm deep for large pads. The resist templates are up to 6% shallower than the protrusion height on the mould. Large pads along the circumference of each die affect the duplication of gates. We used large imprint pressure and thick resist film to achieve good duplications of features with quite different dimensions simultaneously.

In summary, we investigated the pattern transfer fidelity of NIL on a six-inch wafer scale. The CDs of gate patterns in resist are 5.2% (or 37 nm) on average larger than those on the mould with a standard deviation of 1.2% (or 8 nm), and the CDs after oxygen RIE and metal lift-off are 42% (or 296 nm) on average larger than those on the mould with a standard deviation of 8% (or 30 nm). Compared with conventional photolithography, NIL has higher resolution and better pattern transfer fidelity with CD controls about four times smaller.

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