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Nano-scale Patterning by AFM Lithography

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We report on the reliability and minimum pattern size of an atomic force microscopy (AFM) lithography with constant-current-exposure feedback system. The fabricated patterns were uniform. The lifetime of the tip coated with TiN was more than 1 m. We were able to fabricate 15-nm-wide space patterns and 20-nm-wide hole array patterns in a 50-nm-thick resist film by using the spaces between the negative-type resist patterns. The 340-nm thick patterns with linewidth of 50 nm were fabricated by using a multilayer resist method.

Key words: AFM, SPM, nanolithography, resist, multilayer resist system

1. INTRODUCTION

Recently, new devices that use a function of a molecule or an atomic wire have been proposed. Such devices require a fabrication method that can make from nanometer- to micrometer-level structures. Scanning probe microscopy (SPM), such as scanning tunneling microscopy (STM) and atomic force microscopy (AFM), is effective tool for making nanometer-level structures. The SPM lithography method, which uses an organic resist film, is especially useful because it can use various pattern-transfer methods such as etching, plating, and lift-off.

We have developed an SPM lithography system based on AFM (AFM lithography) [1,2]. AFM lithography has certain advantages over STM lithography. For example, patterns can be drawn even on an insulating surface made of organic resists.

In this paper, we describe the features of the developed AFM lithography system, focusing on its reliability and minimum pattern size.

2. EXPERIMENTAL

Figure 1 shows the schematic diagram of the developed AFM lithography system [1,2]. The vertical position of the tip is controlled by a contact-mode AFM system, and the resist is exposed to a field-emission current between the tip and the substrate. The system also had an additional feedback system for adjusting the negative bias voltage applied to the tip to control the field emission current constant.

The tips, which were made of Si and Si_3N_4, were coated with several kinds of conductive materials, such as Ti, TiN, Pt-Pd, and Cr, by DC sputter deposition. Commercially available diamond-like carbon (DLC)-coated tips (Nanosensor) were also used.

A negative-type resist RD2100N (Hitachi Chemical Co.) was spin-coated onto the surface of the sample. The exposure current and the bias voltage to obtain the current values were from 5 to 30 pA and from 10 to 100 V, respectively. The scanning speed of the tip was from 0.01 to 0.1 mm/s. After patterning exposure, the samples were developed by using NMD-W (Tokyo Ohka Kogyo). The developed resist pattern was observed with a scanning electron microscope (SEM).

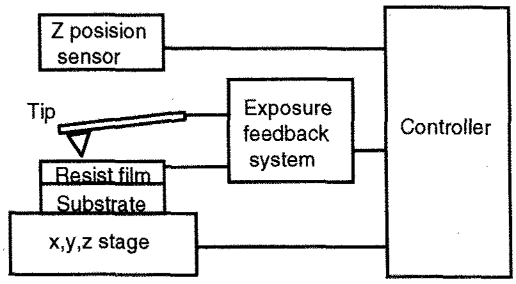

Fig.1 Schematic diagram of the developed AFM lithography system

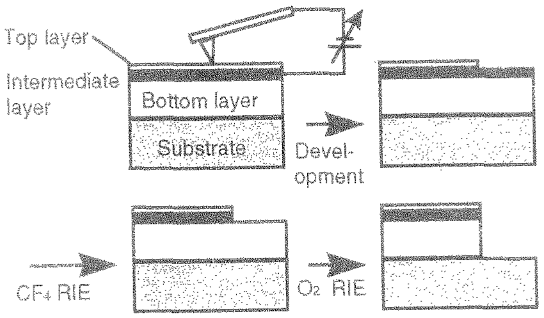

Fig.2 The process flow of AFM lithography with multilayer resist method

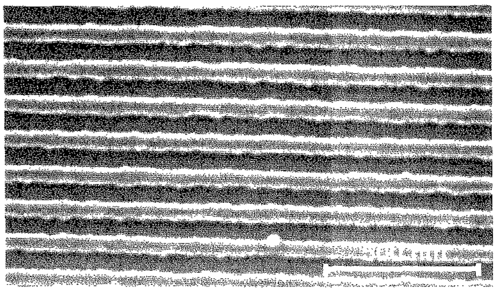

Fig. 3 The SEM micrograph of line-and-space resist pattern fabricated using AFM lithography with constant current controlled exposure feedback system.

The process flow of the multilayer resist method is shown in Fig. 2 [4]. We use the resist RD2100N, sputtered Si, and bottom leveling opaque coat (BLOC) [6] as the top, intermediate, and bottom layers, respectively. The top AFM lithography pattern was transferred to the intermediate layer by using reactive ion etching (RIE) with CF_4. The patterns were transferred to the bottom layer by using O_2 RIE.

3. RESULTS AND DISCUSSION

3.1 Reliability

Figure 3 shows the SEM micrograph of line-and-space resist patterns fabricated using AFM lithography with constant-current-controlled exposure feedback system. The thickness of the resist film was 40 nm, and the exposure dose was 6 nC/cm. The linewidth of patterns were uniform [1-3]. Whereas the linewidth variation in the pattern fabricated by a constant-bias-exposure feedback system is more than 20 nm, the variation in the pattern fabricated by the constant-current-exposure feedback system was less than 5 nm.

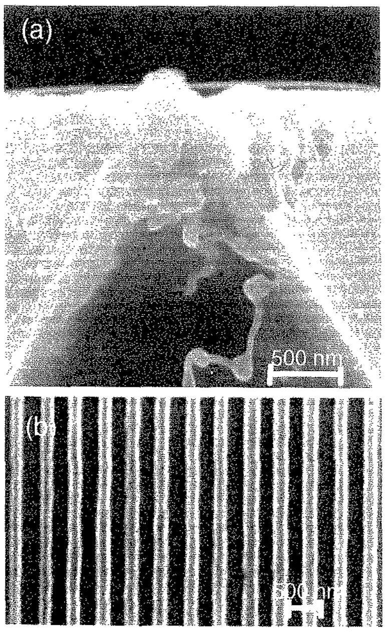

Fig. 4 SEM micrograph of (a) the top shape of the tip after 30-mm patterning, and (b) the resist pattern fabricated by this tip.

Table I Lifetime of tips coated with canductive materials

Material	Thickness (nm)	Life time (cm)
TiN	100	>100
DLC	100	~10
Ti	60	~5
Pt-Pd	40	<1
Cr	20	<1

Figure 4(a) shows the SEM micrograph of the top of the tip after 30-mm patterning, and Fig. 4(b) shows the resist pattern fabricated by this tip. The thickness of the resist film was 40 nm, and the exposure dose was 6 nC/cm. A 10-nm Ti-coated tip was used. The linewidth and uniformity of the resist patterns were constant even though some of the resist film was deposited on the tip, which changed the tip's shape.

These results indicate that the constant-current-exposure feedback system can keep the exposure dose constant, even if the shape of the tip changes or the thickness of the resist film is not uniform.

The lifetimes of the tips coated with several conductive materials are summarized in Table I. The lifetime of a tip was defined as the time when the top shape of the tip changed on the 100 nm level, even if this change produced no change in the fabricated patterns. The thickness of the resist films was 50 nm, and the patterning speed

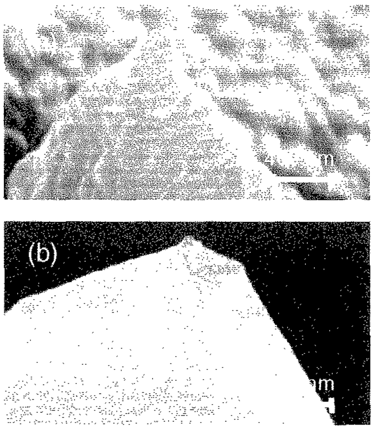

Fig. 5 SEM micrograph of (a) DLC-, coated tip and (b) TiN-coated tip

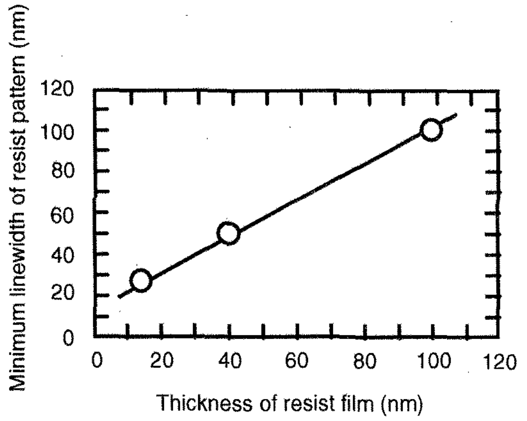

Fig.6 The dependence of the minimum linewidth on resist thickness.

of the tips was 0.1 mm/s. Table I indicates that tips coated with hard materials, such as TiN and DLC, have longer lifetimes compared with tips coated with normal metals. The lifetime of the TiN-coated tip was the longest, even though the hardness of DLC (7000 kgf/mm^2) is higher than that of TiN (2000 kgf/mm^2). This result is attributable to the shape of the DLC-coated tips. Figure 5(a) shows the SEM micrographs of the DLC-coated tip and Fig. 5(b) shows the SEM micrographs of the TiN-coated tip. As is shown in Fig. 5(a), there are many grains on the surface, therefore it is easily broken at cracks between grains.

We estimated that a TiN-coated tip has a lifetime of more than 1 m. This lifetime is long enough that 32 patterns of 50 μm × 50 μm patterns (80-nm pitch) can be fabricated without having to change the tip.

3.2 The minimum pattern size

3.2.1 The dependence of the resolution on resist thickness

Figure 6 shows the dependence of the minimum linewidth on resist thickness [2]. The minimum linewidth was 27 nm. However, the resolution depended on the resist thickness. The aspect ratios were all approximately 1, and therefore, a thin resist is required to fabricate finer patterns. However, it is difficult to transfer the patterns to the substrate by using a thin resist film. We have proposed two new methods of fabricating finer patterns with a thick resist films.

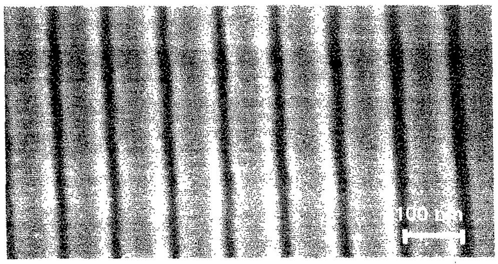

Fig. 7 SEM micrograph of line-and-space resist patterns with pitches from 80 to 100 nm.

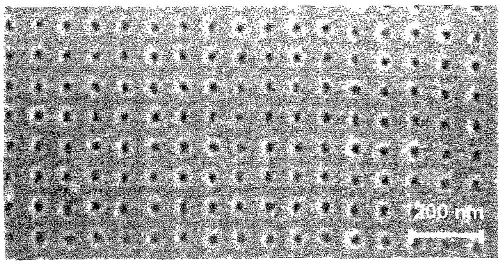

Fig. 8 SEM micrograph of hole array resist patterns

3.2.2 Using the spaces in the resist patterns

When the pitches of the line-and-space patterns becomes smaller, the width of the spaces can be made smaller than the linewidth. The resist thickness cannot limit the width of the spaces. In this manner, we can fabricate a fine pattern.

Figure 7 shows the SEM micrograph of line-and-space resist patterns with pitches from 80 to 100 nm. The thickness of the resist film was 50 nm. The widths of the space patterns become narrower since the widths of all the resist line patterns are the same. A minimum space pattern of 15-nm width were obtained by using a 50-nm-thick resist. The linewidth variation in the resist patterns fabricated by current-controlled AFM lithography are less than 5 nm in a 50-nm-thick resist film. In this way, we obtained 10-nm-level space patterns without any breakage[5].

Figure 8 shows the SEM micrograph of the hole-array resist patterns. These patterns were fabricated by vertical and perpendicular drawing of line-and-space patterns with a negative-type resist. We fabricated an array of holes whose widths were 20 nm with a 50-nm thick resist.

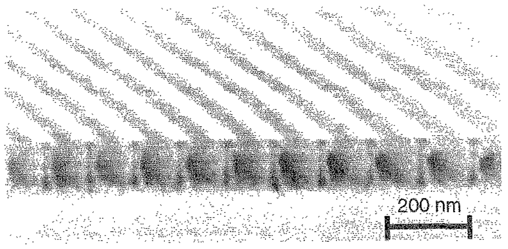

Fig. 9 SEM micrograph of the line-and-space resist patterns fabricated by using AFM lithography with multilayer resist method.

3.2.3 Multilayer resist method

AFM lithography with multilayer resist method has the following advantages.

1. High-resolution and high-aspect-ratio resist patterns can be fabricated because a thin, high-resolution resist can be used as the top layer, when the whole trilayer resist film is thick.
2. The patterns can be formed on the stepped surface because the bottom layer makes the stepped surface planar in shape.
3. Patterns can be formed even if the substrate is an insulator because the top layer is patterned using the current supplied by the bias voltage between the tip and the intermediate layer.

Figure 9 shows an SEM micrograph of the line-and-space resist patterns fabricated by using the AFM lithography with multilayer resist method. The fabricated patterns had linewidths of 50 nm and were 340-nm-thick, the aspect ratio was approximately 7 [4].

4. CONCLUSION

We have reported the reliability and the pattern size characteristics of the developed AFM lithography system with the constant-current-exposure feedback system. We were able to obtain uniform linewidth patterns by using the AFM lithography system. The lifetime of the tip coated with TiN was more than 1 m. The 340-nm thick patterns were fabricated with linewidth of 50 nm and aspect ratio of 7 by using a multilayer resist method. We were able to fabricate 15-nm-wide space patterns and 20-nm-wide hole array patterns in a 50-nm-thick resist film by using the spaces between the negative-type resist patterns.

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