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Optimization of Bi-layer Lift-Off Resist Process

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Abstract

Bi-layer lift-off metallization techniques offer significant advantages in resolution, removal, process simplicity, undercut control and yield over conventional single-layer lift-off processes. Because of its ease of application, long shelf life and lower tool cost, the polydimethylglutarimide (PMGI) bi-layer process has become an attractive method for the metallization of III-V compound semiconductor devices. The LOR/PMGI bi-layer lifts-off cleanly when fabricating source, drain or T-shaped gate ohmic contacts for gallium arsenide (GaAs), GaN, InP and other compound semiconductor devices. Because of its excellent undercut control, LOR/PMGI can be removed in either conventional photoresist removers or in low temperature, metal-ion free aqueous alkaline developers.

Because LOR/PMGI is used with such a wide variety of photoresist and process conditions, a comprehensive process optimization has never been implemented. Therefore, the purpose of this paper is to explore and optimize several key process parameters for controlling the critical dimensions (CD) of the MicroChem LOR/PMGI bi-layer process. LOR/PMGI coatings as thin as 0.20 μm , for the production of 0.45 μm metallic features, and as thick as 3.0 μm , for the production of thick metal depositions, will be investigated using common process controls, such as: LOR/PMGI bake time, bake temperature, TMAH development time and development method. By optimizing these process conditions, further improvements in resolution can be found.

INTRODUCTION

There are two common methods for producing metal or oxide microstructures for semiconductors, namely; lift-off and etching. Lift-off is known as an additive process as opposed to etching, which is a subtractive process. In the lift-off process, a sacrificial photoresist layer is printed using an inverse mask pattern. The metallic or oxide pattern is created by blanket coating the photoresist pattern with metal or oxide and washing away the sacrificial layer. Any material which was deposited on the sacrificial layer is removed, while any material which was in direct contact with the substrate remains. In the etch process, a metallic pattern is fabricated by first blanket coating the substrate with metal or oxide, then patterning photoresist with the desired mask pattern and etching away the metal or oxide not covered by the photoresist. Wet chemical etching is common, but these processes are isotropic and can easily undercut the photoresist. Dry etching is also available, but requires

reactive ion plasma tools. After etching, the photoresist is usually removed in a solvent bath.

There are several different lift-off processes, which are all compatible with both e-beam and sputtering techniques. However, depending on the lift-off material used, retention, "tails", "tears", "flagging" or "fencing" can occur. Retention is the unwanted metal pattern that remains on the wafer and that did not lift-off. This usually happens when the photoresist is completely covered by metal, leaving no gap in the metal coating for the solvent to penetrate and dissolve the photoresist. Flagging or fencing refers to a defect where the gap between the metal on top of the photoresist and the metal on the substrate is small or very thin.¹ In such a case, the metal on top of the photoresist dissolves, but is ripped away from the metal on the substrate, leaving a ragged pattern or "flag" behind. Such pattern irregularities eventually lead to shorts and device failures.²

One lift-off technique, known as bi-layer, uses a coating of LOR/PMGI, which is not photosensitive but is freely soluble in conventional aqueous TMAH developers. Typically, the LOR/PMGI is coated on the substrate first, followed by the photoresist coating. Because of the chemical properties of LOR/PMGI, no intermixing occurs with the subsequent photoresist coating. After imaging, the photoresist and LOR/PMGI are developed at the same time. Once the photoresist is fully developed and the dissolution of the photoresist stops, the developer continues to dissolve away the LOR/PMGI layer in the open areas. Therefore by slightly increasing the standard photoresist developer time, the LOR/PMGI undercut can be tailor-made to suit the deposition requirements. The developer dissolution rate proceeds isotropically, but can be very tightly controlled to "cut under" the edge of the resist profile. This makes LOR/PMGI well suited for critical level lift-off processes where precise undercut control is required.

DEVELOPER CONTROL

The degree of photoresist undercut in a bi-layer process can be controlled using several different parameters in the development process, namely; development time, developer strength, developer type and wafer spin-speed (agitation). Undercut can be defined as the distance between the leading edge of the photoresist pattern and the edge of the LOR structure where it contacts the substrate.

Variables for Spray Development

Substrate agitation was one of the experimental variables tested using a constant developer time for a thick LOR coating. The photoresist and LOR coating was spray developed at various spin speeds with a 60 second development time to observe the effect of undercut profile for thick LOR. Both the amount of undercut and the undercut profile changed with spin speed of the spray develop process.

Figure 1 below shows the effect of wafer spin-speed on the amount of undercut for a 60 second development time. Table 1 shows the undercut measurements taken from the SEM images. From this graph it can be seen that even for a fixed development time of 60 seconds, undercut can be controlled at the rate of 1 $\mu\text{m}/100 \text{ rpm}$ of wafer spin-speed.

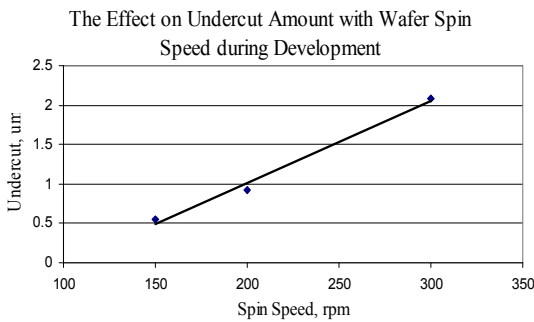


Figure 1 - Spray Develop - Substrate Agitation at constant spray time

With increasing wafer spin-speed during development, not only does the amount of undercut change, but also the undercut profile (Table 1). As the amount of undercut increases, the LOR/PMGI side-wall profile tends to become more vertical.

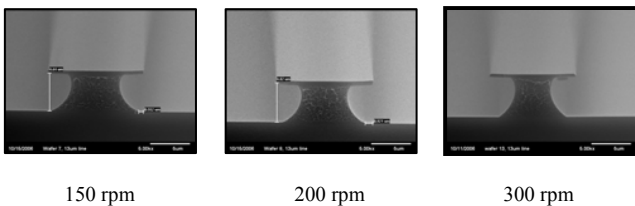


Table 1 – Spray Develop Profiles for thick LOR - increasing wafer spin-speed with constant spray time

Another developer variable which we examined was the developer spray time. In this experiment, the photoresist-LOR bi-layer was spray developed at various develop times and with a constant spin-speed of 150 rpm. Table 2 shows the impact of developer time on both the amount and the shape of the undercut profile, in this spray develop process.

In this evaluation, the developer time was observed to have a significant impact on the amount of undercut. Figure 2 shows that for a fixed substrate spin speed of 150 rpm, undercut can be controlled at the rate of $\sim 0.17 \mu\text{m}/\text{second}$ of

developer time. Therefore, in much the same way that increasing developer agitation influences the undercut amount and profile, increasing developer time does so as well (Table 2). In addition to controlling the amount of undercut, it was also found that the side-wall profile tends to straighten up and have less tailing at the base.

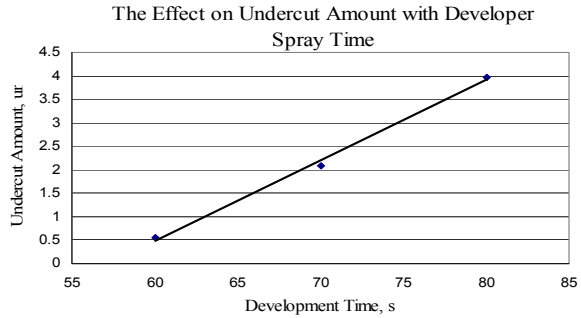


Figure 2 - Spray Develop –Developer time with constant wafer spin-speed of 150 rpm

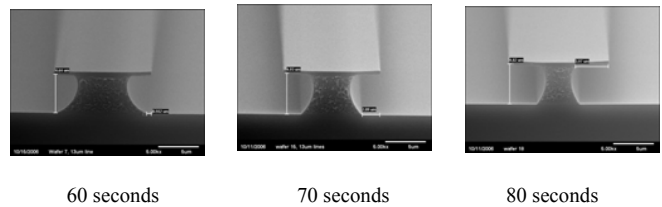


Table 2 – Spray Develop Profiles for thick LOR - increasing develop time with constant wafer spin-speed

The effect of developer spray time on much thinner LOR coatings is shown below in Table 3. For this evaluation, a $0.23 \mu\text{m}$ coating of LOR was applied, followed by a $1 \mu\text{m}$ coating of Rohm & Haas SPR 220-1.0 photoresist. Although the LOR coating had only one-fifth the film thickness, the same trends in undercut and undercut profile with developer time were observed.

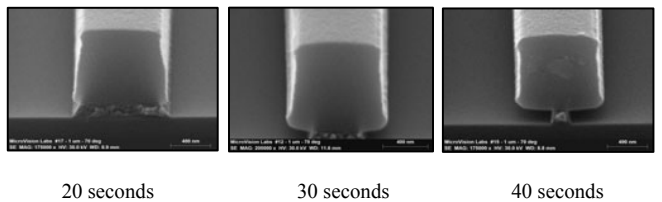


Table 3 – Spray Develop Profiles for thin LOR - increasing develop time with constant substrate agitation

DEVELOPER CONCENTRATION (NORMALITY)

Tetramethyl ammonium hydroxide (TMAH) is perhaps the most widely used developer type for positive, i-line photoresists and is most commonly available at a concentration of 2.38% (0.26N). A lower concentration of 2.2% TMAH is also available and most commonly used for

sub-micron thick coatings of positive i-line photoresists. Figure 3 shows the impact of two common TMAH developer concentrations and bake temperatures on LOR dissolution rate, an analytical measurement of undercut. Dissolution rate is a measurement of film thickness as a function of time in contact with the developer solution. It is often an effective tool for predicting undercut rate using a variety of LOR processing conditions.

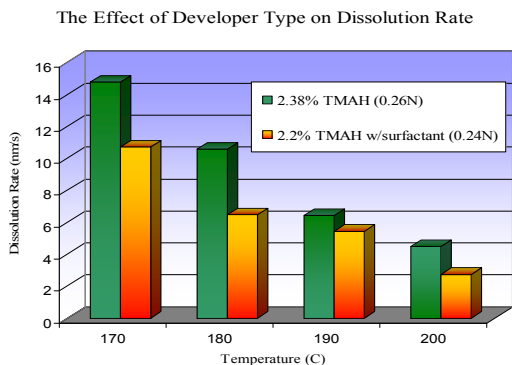


Figure 3 – Dissolution Rate at various LOR soft bake temperatures with different developer concentration (normality)

BAKE TIME AND TEMPERATURE

The bi-layer process can also be effectively controlled with the LOR soft bake time and temperature. Higher soft bake temperatures and longer times tend to produce slower undercut rates. First, more solvent removal takes place at the higher temperatures; and second, by heating the PMGI during soft bake, such that it passes through its glass transition temperature (Tg), the film coating becomes more dense and further decreases the undercut rate.

Table 4 shows the undercut profiles at a constant soft-bake temperature of 200°C and various soft bake times for a thin LOR coating of 0.23 μm. As you can see from the plots in Figure 4, the soft bake temperature has a much larger impact on undercut rate than the soft-bake time.

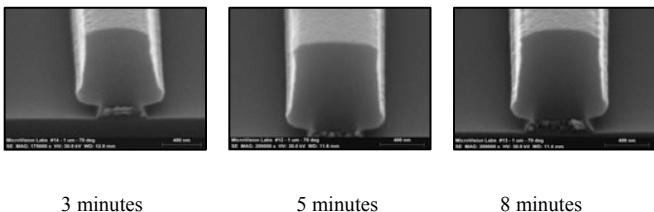


Table 4 – Develop profiles for thin LOR - increasing soft-bake time at constant soft-bake temperature

GLASS TRANSITION TEMPERATURE (Tg)

The glass transition temperature of PMGI was measured by differential scanning calorimeter (DSC) to be between 180 – 210°C as shown in Figure 5. Figure 6 shows that as LOR soft bake temperature increases, the dissolution rate decreases until the glass transition temperature is reached. After that, very little decrease in dissolution rate is

measured, hence little or no dependence of undercut rate with bake temperature is found above the Tg of PMGI.

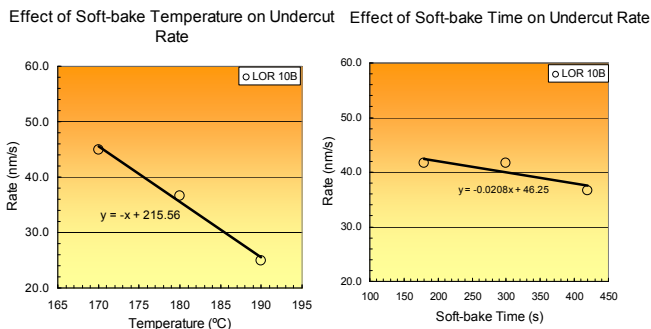


Figure 4 – Comparison of soft-bake temperature versus soft-bake time for a 1 μm LOR film

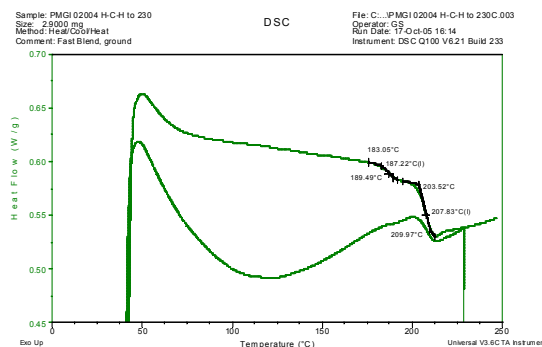


Figure 5 – Glass Transition Temperature (Tg) of PMGI

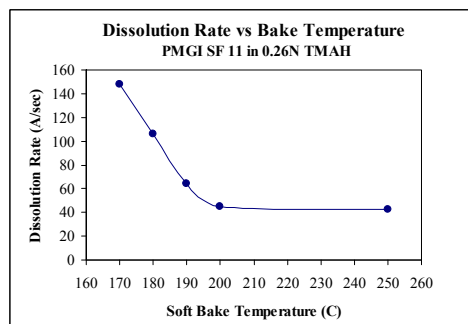


Figure 6 – Dissolution rate vs. bake temperature through the glass transition temperature

FORMULATION

The composition of the LOR can have a pronounced effect on the undercut rate. By careful design of the LOR formulation, the dissolution rate can be precisely controlled over a very wide range. Table 5 shows the relative dissolution rates of several LOR formulations for a 1 μm coating soft baked at 180°C for 5 minutes

METAL DEPOSITION

There are three common methods for metalizing semiconductor devices, namely; sputter, e-beam and electroplating. Sputtering and e-beam are perhaps the most common CMOS compatible methods, while electroplating is

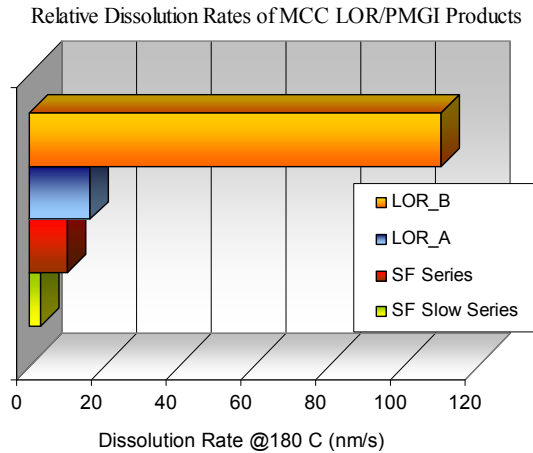


Table 5 – Dissolution Rate control for a 1 μm film soft baked at 180°C for 5 minutes

not as common. Each metallization method has its own characteristics, making the design of a lift-off resist even more challenging.

Because e-beam deposition is anisotropic, the amount of resist undercut is not as critical as with sputter deposition, which tends to deposit the metal isotropically (everywhere). However, not only is it desirable to control the amount of undercut, but by controlling the *height* of the undercut (via the LOR coating thickness); the metal deposition thickness can be accommodated without producing any flagging or fencing.

Figure 7 shows a series of images depicting the entire metallization lift-off sequence, namely; photolithography, e-beam metal deposition and lift-off resist removal. Figure 8 shows that the gold metal deposition of 0.3 μm actually exceeds the 0.23 μm LOR film thickness. A clean lift-off was still possible because the LOR material produced a discontinuity or break in the deposited metal pattern allowing for the solvent to easily penetrate and cleanly lift-off the LOR and the metal.

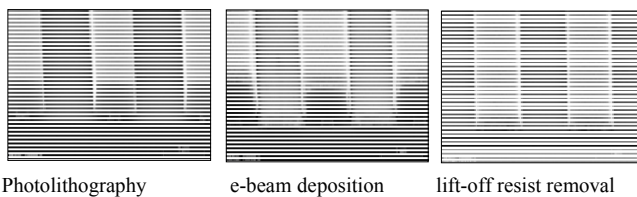


Figure 7 – Bi-layer lift-off metallization sequence

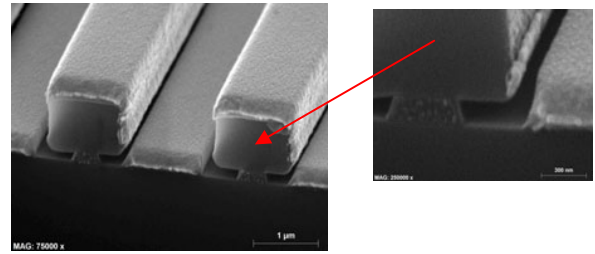


Figure 8 – Bi-layer lift-off in e-beam metallization of gold – discontinuity in the deposited metal allows for complete lift-off removal of resist

SUMMARY AND CONCLUSIONS

Key parameters for controlling critical dimensions in LOR/PMGI bi-layer lift-off processes were explored. Development, soft bake and formulations were optimized for thick and thin LOR coatings. Choice of metal deposition method for bi-layer lift-off was also tested. Several optimization trends were observed in the experiments.

Increased development time and increased wafer spin-speed (agitation) both showed increased levels of undercut. Side-wall profile became more vertical with increased undercut in these cases. Increasing the concentration of TMAH in developer also increased the dissolution rate and the amount of undercut.

As bake time and temperature increased, the undercut rate of the LOR decreased. Bake temperature had a much greater influence on undercut rate than did bake time. The glass transition temperature of the PMGI was explored to explain why the undercut rate was nearly linear above the Tg.

Metal deposition in bi-layer systems provides discontinuity of the metal for e-beam and sputtering. This gives excellent deposition profiles by eliminating the problems of flagging or fencing.

ACRONYMS

LOR: Lift Off Resist
 PMGI: Polydimethylglutarimide
 TMAH: Tetramethyl ammonium hydroxide
 Tg: Glass transition temperature

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