40 nm T-Gate Process Development using ZEP Reflow

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Abstract

In this paper we discuss the thermal reflow characteristics of ZEP 520A-7 resist and demonstrate its capability to serve as a gate stem definition layer for a sub-0.25 µm T-gate process. By using reflow, we have found that as-developed reentrant ZEP feature sidewalls that are initially negatively-sloped (with respect to the sample normal) can be reshaped considerably to have a significant positive slope. This modification in resist profile reduces metal cathedraling and, subsequently, improves T-gate yield. In addition to profile angle alteration, reflow also causes a critical dimension (CD) reduction that is self-limiting in many cases. For example, at a reflow temperature of 145 °C, the reduction of 100 - 120 nm openings reaches a saturation point after 450 s, resulting in final CDs of 30 – 40 nm. This process has been used to demonstrate 40 nm T-gates on AlGaN/GaN mechanical wafers.

INTRODUCTION

As III-V compound semiconductor technology extends its reach into the millimeter wavelength (MMW) frequency application space, solid-state power amplifier designs rely heavily on the ability to reduce transistor lateral and vertical dimensions while maintaining high yield. In high-electron-mobility transistors (HEMTs), T-shaped gates (T-gates) are often used to simultaneously attain short gate length and large gate cross-sectional area to reduce electron transit delay time and ensure low gate resistance, respectively. To fabricate sub-0.25 micron T-gates that are necessary for MMW transistor operation, e-beam lithography is often used to define either a bi-layer or tri-layer resist stack for metal liftoff. A common problem that occurs as gate stem length is reduced is known as "metal cathedraling," where metal builds up laterally on the top corners of the bottom resist layer feature and eventually results in a narrow junction between the T-gate stem and head. This undesirable junction can lead to poor electrical contact between the stem and head of the T-gate, and in extreme cases can result in low yield due to detachment/liftoff of the gate head from the stem.

In this study we have developed a simple technique that helps improve the yield and design flexibility of sub-0.25 micron T-gates by reflow rounding of the bottom ZEP resist feature in a bi-layer ZEP/UV5 stack. Reflow rounding of resist has been studied previously for gate profile engineering and critical dimension (CD) reduction [1-3], but to the best of our knowledge, this is the first systematic study that investigates ZEP resist reflow for T-gate fabrication. ZEP resist offers potential advantages of having higher dry etch resistance and selectivity to tetramethyl ammonium hydroxide developers. In this study, we have varied process parameters such as ZEP reflow time and temperature, e-beam line dose and aperature to observe their effect on resulting resist profiles.

EXPERIMENTAL

Sample preparation for this study began by spinning Zeon Corporation ZEP 520A-7 resist on a quarter of a 3" Si (100) wafer. The ZEP was spun on at 5000 RPM for 30 s then baked at 180 °C for 3 min, resulting in a film thickness of approximately 235 nm. Sets of 4 mm long lines were then written in the ZEP using a 30 kV Raith150 electron-beam lithography system. Three line doses were used in this study: 0.6, 3.5, and 5.0 nC/cm. After exposure, the sample was developed in n-amyl acetate for 30 s, followed by an iso-propyl alcohol bath for 15 s, and then dried. Figure 1 shows an SEM cross-section of an as-developed feature with 5.0 nC/cm dose with a slightly reentrant profile. The average base angle of the resist feature with respect to the sample normal was -8°.

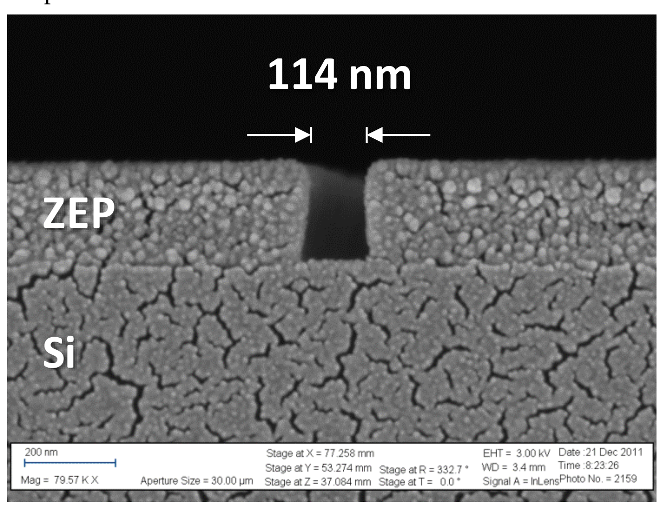

Figure 1 – Cross-section of as-developed ZEP line (dose = 5.0 nC/cm).

After development, the Si wafer was cleaved into numerous samples for ZEP reflow experimentation. Reflow was carried out on samples by using vacuum pull-down on a hot plate that was calibrated with a digital thermometer and type K thermocouple. For all of the samples discussed in this paper, the reflow process was performed only once, i.e. no sequential or cumulative annealing was used on any given sample. Figure 2 shows an example of a 5.0 nC/cm line that was reflowed at 145 °C for 10 minutes. After reflow, the resist profile changed from reentrant to a rounded shape with a base angle of 26°. The line width was also reduced to 37 nm from 114 nm.

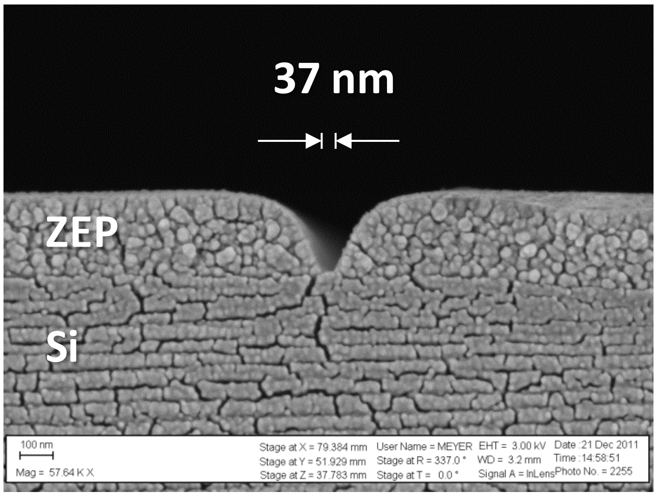

Figure 2 – Cross-section of ZEP line (dose = 5.0 nC/cm) after 10 min reflow at 145 °C.

For the majority of the samples in this study, processing was stopped after ZEP reflow so samples could be cleaved and examined in a field-emission scanning-electron microscope (SEM). To minimize image distortion due to charging, each sample was sputter coated with Au and grounded with Cu tape. The SEM's measurement accuracy was verified to be within 1 % of actual value by using a Ted Pella, Inc. 2 mm – 100 nm CD standard. To investigate the use of the ZEP reflow process in fabrication of T-gates, reflowed samples were coated with Rohm and Haas UV5-0.6 resist at 3000 RPM for 30 s and baked at 120 °C for 1 min. An aligned e-beam lithography area dose (25 $\mu C/cm^2$) was then used to write the T-gate head feature. After a post-exposure bake at 128 °C for 1 min, the sample was developed in CD-26 for 45 s. A low-power, 20 s O_2 plasma descum was performed to remove any remaining residue. Figure 3 shows the resulting UV5/ZEP profile.

After UV5 development, Ni/Au (20/300 nm) metal was deposited by e-beam evaporation, resulting in a cross-section shown by Figure 4. To complete the T-gate fabrication process, the sample was then lifted-off in n-methyl pyrrolidinone. Figure 5 shows an SEM image of a 40 nm T-gate that is formed when using an optimized UV5/reflowed ZEP process on an AlGaN/GaN mechanical wafer.

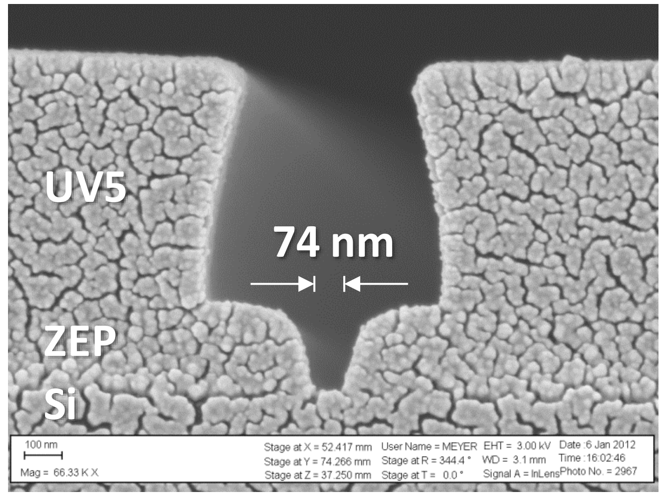

Figure 3 – Cross-section of UV5 feature on reflowed ZEP line (dose = 5.0 nC/cm, 10 min reflow at 145 °C). After development of UV5, a 20 sec O_2 plasma descum was performed.

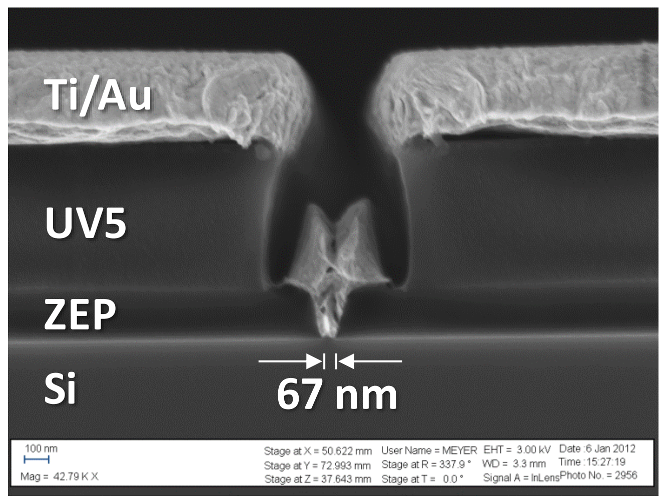

Figure 4 – Cross-section of metalized UV5/reflowed ZEP line (dose = 5.0 nC/cm, 10 min reflow at 145 °C, 20 s O_2 plasma descum).

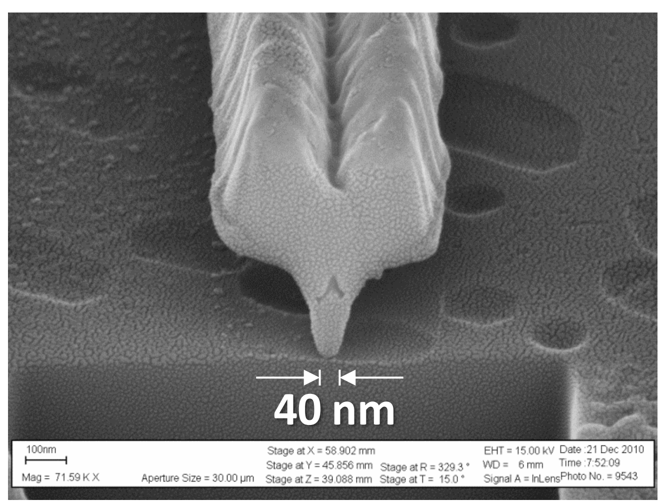

Figure 5 – FIB cross-section of 40 nm T-gate on AlGaN/GaN mechanical wafer. The imaging angle is tilted 30° from the wafer surface.

RESULTS AND DISCUSSION

The primary objective of this study was to determine whether the thermal reflow of ZEP resist could be used in a controllable manner to serve as the basis of a high-yield, sub-0.25 µm T-gate process. To begin this investigation, we initially looked at the effect of hot plate temperature on reflow character. Figure 6 shows ZEP feature CD versus hot plate temperature for a fixed reflow time of 2 minutes. CD was defined as the shortest distance between the two sidewalls of a feature. At temperatures of 140 °C and below, ZEP feature profiles and CD did not change significantly from the as-developed case. At 155 °C significant reflow occurred, which resulted in coalescence of resist from both sides of all features. For the 145 °C and 150 °C cases, reflow caused the CD to decrease for all line doses, with the exception of the 5.0 nC/cm line at 145 °C.

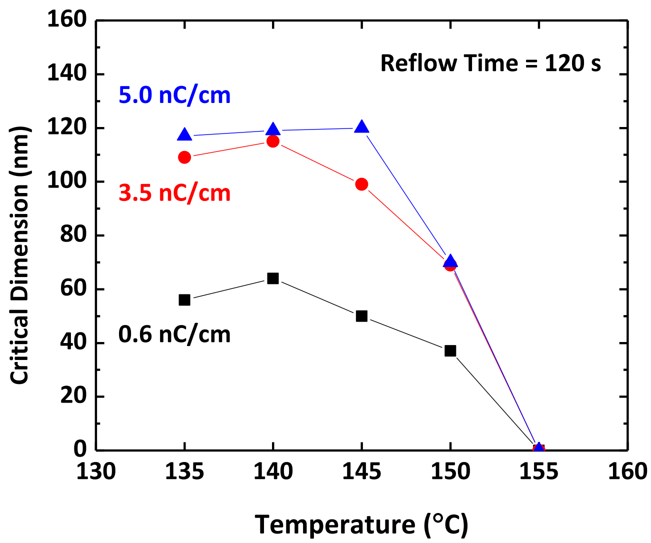

Figure 6 – ZEP feature size as a function of reflow temperature. The reflow duration was 2 min for all samples.

After determining that ZEP reflow would occur in the 145-150 °C temperature window, we proceeded to study the effect of reflow time on feature profile. Figure 7 illustrates the relationship between feature CD and reflow time at 145 °C. While analyzing the cross-sectional images of lines on samples used in Figure 7, we also measured and plotted the base angle of the resist profile with respect to the sample normal and plotted it in Figure 8.

It is interesting to note that although CD does not change significantly in the first 2 minutes of reflow time, the resist profile base angle does shift from negative to positive values. This suggests that the overhanging resist in the initial reentrant profile slowly reflows and extends the base of the feature outward until it reaches equilibrium with the surface and/or undeveloped body of resist. After approximately 450 s, in Figure 7, the CD size appears to settle at 30 – 40 nm for the 3.5 and 5.0 nC/cm lines, corresponding to a similar saturation in profile angle at 24 - 26° in Figure 8. For the smallest dose, reflow caused the feature to close up after 300 s. Saturation of the 3.5 and 5.0 nC/cm line CDs and profile angles are encouraging from a processing standpoint, as it potentially allows us to eliminate the time variable from consideration when developing this reflow process for T-gate application.

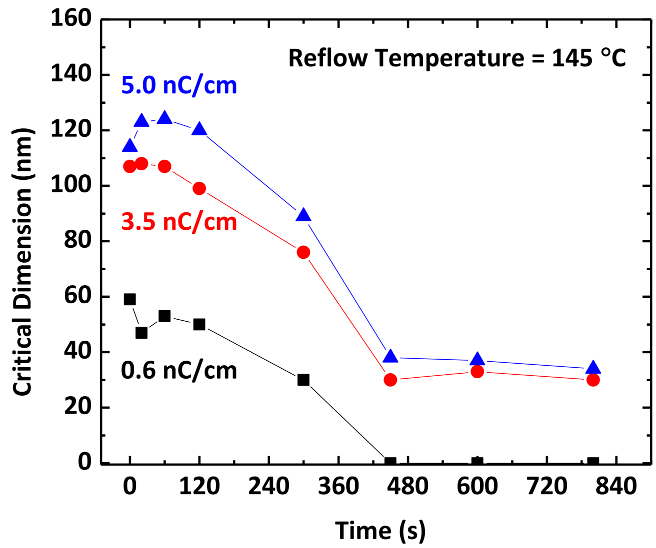

Figure 7 – ZEP feature size as a function of reflow time at 145 °C.

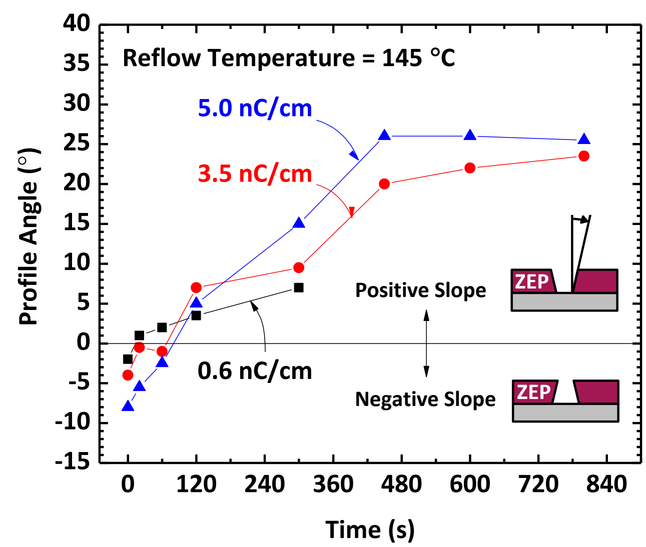

Figure 8 – ZEP feature angle as a function of reflow time at 145 °C.

Upon closer inspection of the data in Figure 8, we noticed that the final profile angle appears to be dependent on the starting base angle of the resist. In order to confirm this relationship between initial and final angle, we processed several samples with a variety of doses and e-beam aperture settings to vary the initial profile angle between -30° and 0°, and then subjected the samples to a 10 minute reflow at 145 °C or 150 °C. Figure 9 shows that there was a distinct correlation between initial and final profile angle for both reflow temperatures used. This relationship may be useful in T-gate profile design, where the gate stem could serve as a slant field plate, similar to those previously fabricated by recess etching and filling of SiN_x features.[4]

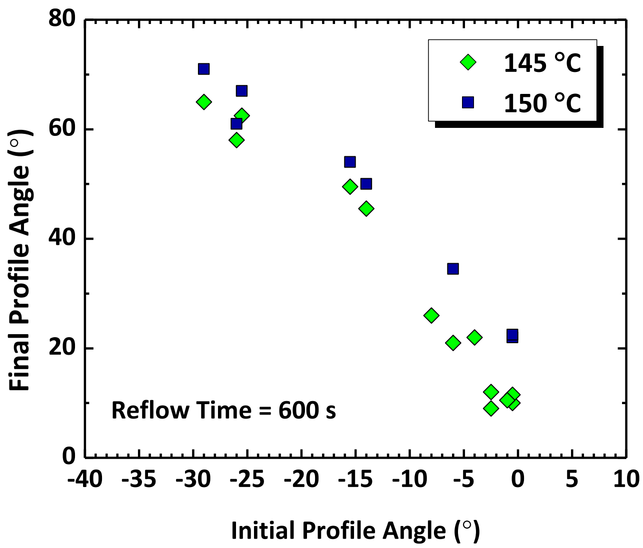

Figure 9 – ZEP feature final angle vs. initial angle for 10 min reflow at 145 °C or 150 °C.

CONCLUSIONS

In this study we have investigated the thermal reflow of ZEP resist features to evaluate its use as a method for defining a stem of a sub-0.25 µm T-shaped gate. We have found that ZEP features reflow at a controllable rate in the temperature range of 145 – 150 °C. At 145 °C, reduction of line width for features with initial CD of 100 - 120 nm reaches a saturation point after 450 s, resulting in final CDs of 30 – 40 nm. At 450 s of reflow time, the resist profile angle also saturates at 24 - 26°. A correlation between initial and final profile angle was observed. With substantial positive profile angles, it is expected that metal cathedraling and, subsequently, gate head yield issues will be minimized. This technique has been successfully applied to AlGaN/GaN mechanical wafers to demonstrate the feasibility of UV5/reflowed ZEP 40 nm T-gates.

ACKNOWLEDGEMENTS

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REFERENCES

[1] H.-M. Lee, E. Y. Chang, S.-H. Chen, and C.-Y. Chang, Jpn. J. Appl. Phys. **41**, L1508 (2002).

[2] Y. C. Lien, E. Y. Chang, H. C. Chang, L. H. Chu, G. W. Huang, H. M. Lee, C. S. Lee, S. H. Chen, P. T. Shen, and C. Y. Chang, IEEE Electron Device Lett. **25**, 348-350 (2004).

[3] C. C. Meng, G. R. Liao, and S. S. Lu, Electron. Lett. **37**, 1045-1046 (2001).

[4] Y. Pei, Z. Chen, D. Brown, S. Keller, S. P. Denbaars, and U. K. Mishra, IEEE Electron Device Lett. **30**, 328-330 (2009).

ACRONYMS

CD: critical dimension
HEMT: high-electron-mobility transistor
MMW: millimeter wave
SEM: scanning electron microscopy