Impact of Loading Effect on Retrograde Profile of CAMP Negative Photoresist in Metal Lift-off Applications

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ABSTRACT

Metal lift-off processes using a chemically amplified negative tone resist have been evaluated for thin and thick metal layers with various degree of success. This limited success is often attributed to the differences in performance characteristics of CAMP negative tone resists as compared to the historic positive tone resists used in image reversal processes. Success of the lift-off process is directly correlated to the negative (retrograde) side wall angle of the resist profile. In this paper, we discuss one of the mechanisms referred to as 'Loading Effect' by which the negative resist materials can behave differently causing variations in the resist retrograde profile and defects associated with it.

INTRODUCTION

Metal lift-off processes have been the main patterning method for metal contacts and interconnects in III-V semiconductor technology for decades. Over the years, there have been significant advancements in the photolithographic process approaches associated with the metal lift-off process. For instance, such approaches include image reversal processes using a positive tone resist. This process is still the main workhorse. It creates a well-defined retrograde profile and thus makes lift-off of evaporated and even sputter deposited layers possible. The retrograde resist profile angle is highly reproducible for this method. Despite its wide acceptance, this approach has its disadvantages such as long cycle times, requirements for space in fab, and oven loading in the NH3 ovens etc. Hence, new negative resists have been developed specifically for the lift-off applications, such as chemically amplified (CAMP) negative tone photoresist.

Lift-off processes using a CAMP negative tone resist have been evaluated for thin and thick metal layers with varied degrees of success. This limited success is often attributed to the differences in performance characteristics of CAMP negative tone resists as compared to the historic positive tone resists used in image reverse processes. CAMP negative tone resists are a relatively newer and more streamlined option for lift-off processes. These resists which were designed for lift-off are able to attain a retrograde resist profile with high reproducibility. This resist profile helps to prevent metal deposition on the resist sidewalls, which makes the subsequent lift-off process easier [1].

PATTERNING CAMP NEGATIVE RESIST

Primary Process Parameters

Success of the lift-off process is directly dependent on the extent of retrograde side wall angle of the resist profile. The retrograde provides the necessary separation within the deposited metal layer sheet [Fig.1]. The chemicals used for the metal lift-off process can then reach and dissolve the resist material under the metal sheet, thereby subsequently lifting it off cleanly.

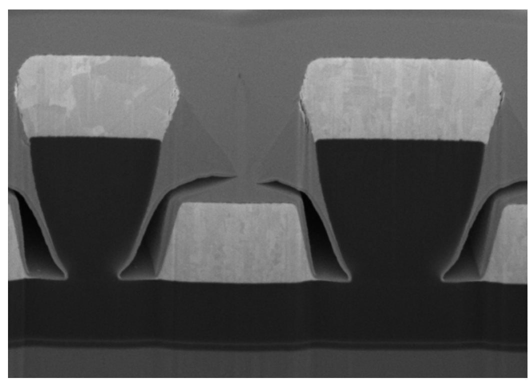

Figure 1: Separation in the deposited metal sheet due to retrograde resist profile

In a lift-off process approach using the CAMP negative tone resist, obtaining and maintaining the retrograde resist sidewall profile is very critical. There are multiple factors affecting the retrograde angle of the resist profile. Primary factors, such as resist thickness, exposure dose, PEB, develop time and optical parameters for exposure can be optimized during the process development [2][3][4]. In achieving the retrograde profile, multiple researchers reported a need for a large defocus on the steppers, to a point where the lens curvature effect becomes significant. Restrictions associated with the lens curvature limit the size of the reticle field. Also, there can be a need for comparatively large reticle bias (or correction factor) and hence the resolution of sub-micron features can become very difficult [5] [6].

The reflection of light from the underlying metal layers during the exposure step turns out to be a significant cause of concern as well. The printed resist lines over the underlying metal behave differently than from the lines printed over less reflective surfaces like silicon nitride or polyimide. Pattern fidelity and resolution is much more sensitive to the photospeed variation for CAMP negative tone resists when compared to the positive resists which requires a tight control over stepper exposure dose. Baseline matching of the exposure dose between the stepper tools becomes an important factor to be controlled. Also, the photospeed changes with aging of the resist material as well as the photospeed variations among different resist batches become a significant factor of concern and needs to be closely controlled.

Secondary Parameters

In addition to optimizing the primary process parameters, there are secondary parameters that have also been found to affect the resist retrograde profile. Such secondary parameters include the topography underneath the resist as well as the circuit layout for a given photo layer. While primary parameters affect the retrograde profile on the global level, secondary parameters affect the retrograde profile at specific sites and locations. The localized retrograde change due to secondary parameters combined with evaporator run-outs can lead to improper lift-off, leaving behind a raised metal flap generally referred to as "metal fencing" [Fig.2] [1].

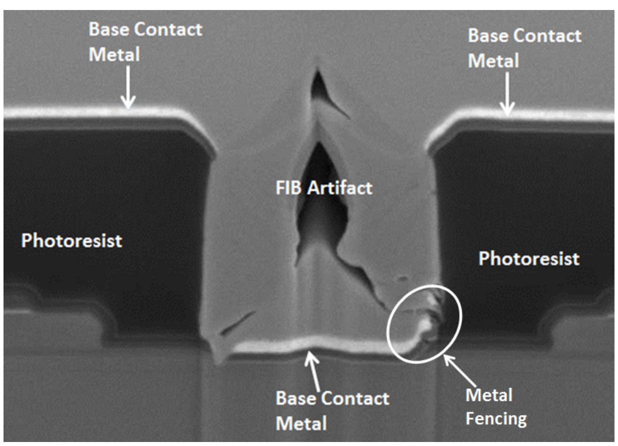

Figure 2: Metal fencing as a result of loading effect

The yield loss associated with these defects can be up to one percent, on average. However, the combined effect of yield loss, loss of productivity and risk of reliability failure makes this a highly critical issue to be resolved. Considering the complexity of current generation III-V devices, high topography devices are inevitable. The effects associated with circuit layout on the retrograde profile were observed and investigated in this work.

EXPERIMENTAL DETAILS

Observation

It was observed that certain features in a given design of a circuit layer showed repeated failure for the metal fencing defect. It was further observed that the given feature failed only in certain locations of a given die. Further investigations revealed that density and proximity of the adjacent features played a critical role in the extent of the failure rate. The circuit layout for a given layer determines how various structures are placed which subsequently created differences in the failure rate.

The circuit layout defines the amount of the bulk of the resist that would be present around a feature. The different amount of the bulk of resist present around a given feature causes the differences in retrograde angle which is referred to as the "Loading Effect". The loading effect can be interpreted as the change in the resist retrograde profile angle as an outcome of the amount of bulk of the resist material surrounding the feature of interest. Two sides of a resist trench can exhibit different retrograde resist wall angles due to the loading effect which leads to asymmetrical metal coverage. The defects associated with the asymmetrical metal coverage can be amplified by the angle of arrival of metal in the deposition system. This then leads to aforementioned "metal fencing" defect. The loading effect can also cause difficulty in controlling the intra wafer CD variation for critical layers such as the gate layer (GL) and the base contact layer (BC).

Experimental Validation

A specific set of test structures were designed to establish and validate the loading effect. In the test structures, the width of the resist bulk line surrounding the resist trench of interest was varied systematically. The layouts for the designed structures were generated for critical layer such as BC and then placed in test products [Fig.3].

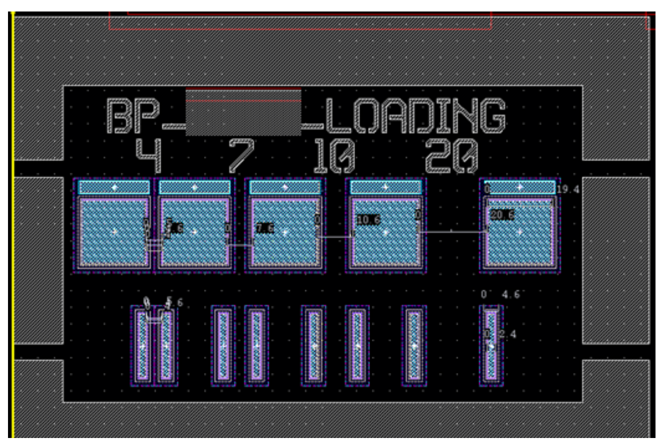

Figure: 3: The layout for designed structures to investigate loading effect at BC

This enabled the investigation of the loading effect for thin metal layers as well as thick metal layers. Test wafers in multiple iterations were processed through the BC layer photolithography fabrication process. After the develop step, FIB cross-sections were taken at each space of varying resist widths. The FIB cross sections taken for the feature of interest were then carefully analyzed and measured for parameters such as resist retrograde profile angle, feature size and resist coverage.

RESULT AND DISCUSSIONS

The FIB images taken at various layers and in multiple iterations confirmed that the resist retrograde angle gets increasingly vertical with increase in the bulk of the resist present around a trench and hence validates the loading effect phenomenon. The parameter of interest, resist retrograde profile angle plotted against width of the resist line is shown in Figure 4. The plot shows that the resist retrograde profile angle is seen to increase towards 90 degrees with an increase in the resist line width surrounding the feature. The retrograde angle changes by over 10 degrees with a change in the resist line width from 4um to 20µm and above, making the resist profile angle almost vertical (90 degrees). In this case, a resist width that surrounds a trench with more than 60µm of size is considered as an infinite. This condition produced almost a vertical resist retrograde profile angle.

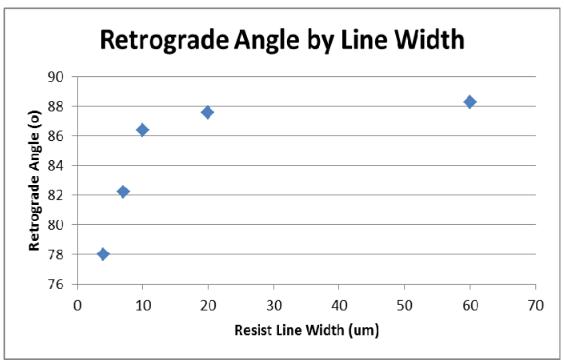

Figure 4: Measured retrograde angle as a function of the width of photoresist

The condition of infinite bulk of the resist present around the trench of interest produces the retrograde resist profile angle of 88.7 degrees making the profile almost vertical whereas, a line width of 2µm surrounding the trench of interest produces a resist retrograde angle of 81 degrees. The difference between these two conditions is almost 8 degrees [Fig.5a].

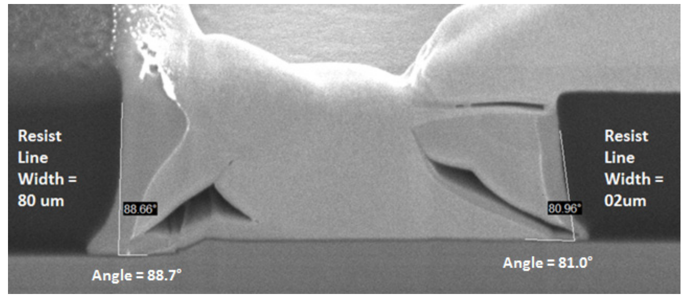

Figure: 5a: FIB cross-section images of retrograde angle for 2µm, 80µm line width

This difference in the retrograde angle is large enough to be able to drive the higher failure rates for metal fencing issues. The corresponding images of the FIB cross sections suggest that the change in resist profile angle is associated with the change in the resist line width [Fig.5b].

For CAMP negative photoresists, the Photo Acid Generator (PAG) is activated when the photons interact with the resist material from the exposure step. During the necessary PEB step, the activated PAG compounds start migrating and leading to the crosslinking of the polymer. When there is a larger bulk of the resist material available, more of the activated PAG compounds are available for the migration and this leads to higher degree of crosslinking. Thus higher the extent of bulk resist material present, greater the loading effect which increases the migration of the PAG, and in turn gives rise to more polymer crosslinking. This higher degree of polymer crosslinking makes the resist less soluble in the developer which causes more vertical profiles.

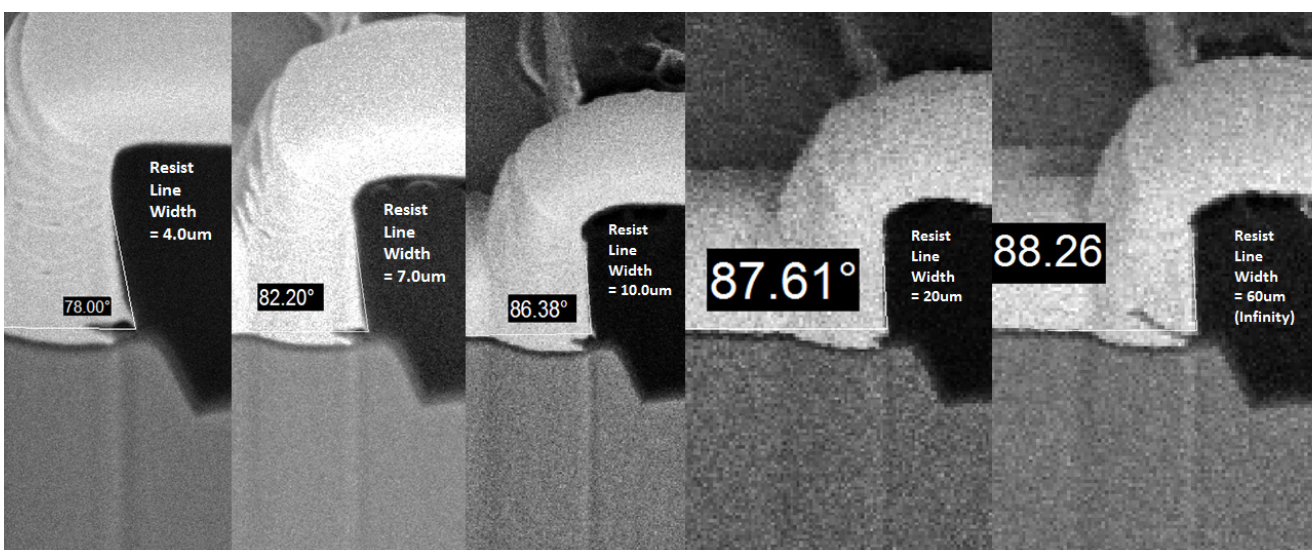

Figure: 5b: FIB cross-section images of the resist retrograde angle with different photoresist widths

CONCLUSION

In summary, despite the several reported challenges, a lift-off process approach using a CAMP negative tone resist was successfully implemented in a high volume GaAs HBT process. The process was developed over the years by carefully resolving the issues that have been reported. The loading effect is a secondary but critical phenomenon to be considered for the successful development of a metal lift-off process using a CAMP resist. The experimental data confirmed and validated the loading effect phenomenon. The data also provides the correlation between defects such as metal fencing to the loading effect. DFM rules have been implemented for avoiding such layouts that can cause issues due to the loading effect. Going forward, we have been collaborating with the photoresist manufacturer to improve the photoresist to minimize the loading effect.

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ACRONYMS

CAMP: Chemically Amplified
CD: Critical Dimension
PEB: Post Exposure Bake
GL: Gate Layer
BC: Base Contact
GaAs: Gallium Arsenide
HBT: Heterojunction Bipolar Transistor
PAG: Photo Acid Generators
FIB: Focused Ion Beam
DFM: Design for Manufacturability