Evolution and Challenges of a TaN Resistor Lift-off Process from a Lithography Perspective

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ABSTRACT

This paper will describe the evolution of various lithographic processes that were aimed at fabricating robust TaN resistors in BiFET and BiHEMT technologies. Such approaches include an image reverse photo process (via amine poisoning) using a positive tone resist, the use of a CAMP (chemically amplified) negative tone resist, and also straight patterning of a positive tone resist. The aforementioned approaches were found to have their own unique challenges as it applied to printing robust TaN based resistors. We will explore many of these challenges in detail for the various lithography schemes.

INTRODUCTION

High TCR (Temperature Coefficient of Resistance) and low current-carrying capabilities of semiconductor resistors are unacceptable for today's GaAs power amplifier requirements. Thus, thin film resistors (TFRs) are required for most III-V semiconductor IC applications. Tantalum Nitride (TaN) based resistors are very stable, preferably deposited by sputter deposition and can be patterned with an array of lithography approaches. [1]

Since the TaN film is deposited via reactive sputter deposition, controlling various aspects of the resist process are critical for meeting TaN resistor specifications. These intrinsic process parameters include resist thickness control over various topographies for a given technology, CD control at the top and bottom of the resist openings, as well as sidewall angle and shape of the resist profile which need to be carefully tailored in order to sustain a robust TaN lift-off process. Additional extrinsic concerns that need to be considered are the total cost of the photo process, the cycle time and overall throughput of the photo module, and the resultant yield of a given lithographic approach for TaN patterning.

EVOLUTION OF TaN PATTERNING

Approach 1: Positive Resist, Image Reverse Process

An image reverse photo process using a positive tone DNQ/Novolac i-line resist was one of the first approaches deployed for the patterning of TaN resistors. This approach has a long history and was the work horse for TaN lift-off patterning for many years. The image reversal is accomplished by using an NH_3 bake step in a convection oven soon after the indene carboxylic acids are generated during the initial expose step. The post expose NH_3 bake neutralizes the carboxylic acids and acts as a gradual diffusion front starting from the top surface of the resist down into the bulk. This renders the initially exposed region insoluble and the NH_3 gradient acts as the precursor to the required retrograde profile. The NH_3 bake is then followed by a blanket flood exposure just prior to the final develop step. This in turn provides an inverse polarity resist image with a negative sidewall profile for subsequent TaN lift-off.

This process had both advantages and disadvantages. As long as input parameters were stringently met, this process was rather stable in terms of CD control. This was a major benefit for printing TaN resistors with good repeatability within wafer, wafer to wafer, and from lot to lot. However, cycle time through this process was very high as it required multiple steps to perform the image reversing of the resist polarity. The NH_3 convention bake was quite long (>100min) and resist behavior was very sensitive due to loading effects during the NH_3 bake. The total surface area of the wafers within a given run, as well as the positioning of the cassettes within the convection oven had to be tightly controlled in order for CD's and resist profiles to remain nominal. The subsequent flood expose step required an additional module on the develop tool and this also had an adverse effect on cycle time. Another drawback to this process were the standing waves in the resist profile which was the result of not having a PEB (Post Exposure Bake) step to normalize the photo acids along the boundary between the exposed and unexposed regions. These standing waves would allow the thin film of TaN metal to be deposited conformally along them which resulted in TaN coils or "TFR wings" which were very difficult to remove during the subsequent lift-off operation. These TFR wings could impact yield as they would result in open circuits due to discontinuous first metal interconnects wherever the wings were present. This is illustrated in Figures 1A and 1B.

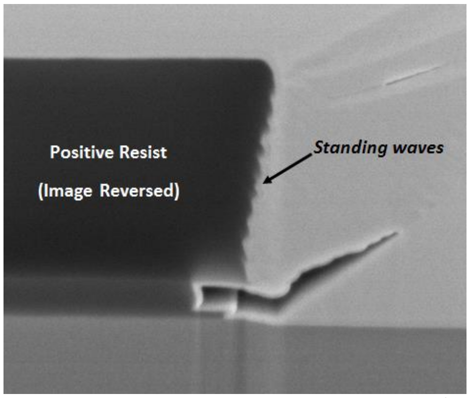

Figure 1A. Resist standing waves along sidewall of positive tone image reversed resist prior to TaN deposition.

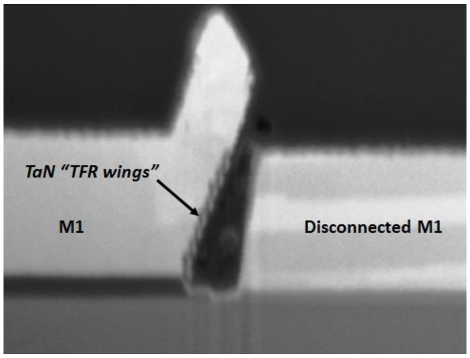

Figure 1B. Resultant TaN wing formation and subsequent discontinuity in Metal1 interconnect traces.

Approach 2: Negative CAMP Resist Process

To eliminate the TFR wing yield concern, as well as decrease cycle time of the TFR photo process, a CAMP (Chemically Amplified) negative tone photoresist process was deployed. This process was able to utilize the existing clear field reticles previously used for the image reverse process. However, this approach also had its pros and cons. In regards to cycle time, both the NH_3 bake and subsequent flood expose steps were no longer necessary so this helped to increase the throughput for the TFR photo module. Furthermore, since this negative tone resist was chemically amplified, newer model tracks were brought in to accommodate the stringent PEB step and these tracks were also much faster. Streamlining the process in conjunction with newer equipment had a significant impact on throughput (~ 57% reduction in 1X theoretical cycle time) thereby allowing the move goals of the photo area to be met. This is illustrated in Table 1.

TABLE 1: CYCLE TIME COMPARISONS

Positive Resist (Image Reversal)		Negative Resist (CAMP)	
Pocess Steps	**T.P. (WPH)**	**Pocess Steps**	**T.P. (WPH)**
Coat	77.8	Coat	77.8
Expose	59.3	Expose	69.8
NH_3 bake	34.3		
Flood Exp/Develop	31.6	Develop only	94.8
1X Cycle Time (min)	**5.4**	**1X Cycle Time (min)**	**2.3**

Since the negative tone resist was chemically amplified, the required PEB step had to be carried out on a very tightly controlled hotplate and it also resulted in smoother sidewall profiles (no standing waves) which were found to help eliminate the TFR wing issue. The dynamics in how the negative resist dissolved during the NMP lift-off step also helped to eliminate the TFR wings. The heavily crosslinked polymer resulted in a glassy material which tended to shatter in the presence of hot NMP during the TaN lift-off step. This caused any TaN deposition along the sidewalls of the resist to be fully removed, unlike the positive tone image reversal resist that dissolved around the TaN metal along the sidewalls and left them intact.

Though cycle time and the TaN wing yield concerns were resolved with this new negative tone approach, it also came with its own set of challenges. Martinez et al [2] found that process margin for their smallest linewidths (5um) did not meet expectations. They concluded that it was not possible to achieve good results with any combination of exposure, focus or bake temperature as variations of 20% in linewidth were observed. In spite of these challenges, an optimized photo process is able to achieve acceptable control for a 2um wide TaN resistor. Nevertheless, CD control was no longer as stable as the previous image reverse scheme. This led to more variation in TaN resistor values. Furthermore, since the negative tone process relied on chemical amplification of photo acids and subsequent crosslinking of the polymer system during the PEB step, NMP lift-off became an issue in terms of filter clogging and shorter filter lifetime across lift-off tools.

Lastly, we found that the rheology of the negative tone resist was very planarizing, which resulted in resist coverage issues for newer BiHEMT technologies that inherently had more aggressive topography. The lack of adequate resist coverage over transistors sitting at higher topographies resulted in complete resist erosion during a fluorine based dry etch step prior to TaN deposition. This resulted in open circuits where metal1 interconnects were unable to pass through vias that were blocked by TaN metal straps [3] as illustrated in Figures 3A and 3B below.

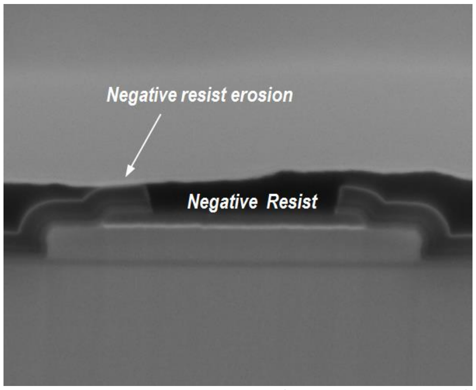

Figure 3A. Negative tone resist fully eroded on top of HBT after fluorine based dry etch (prior to TaN deposition).

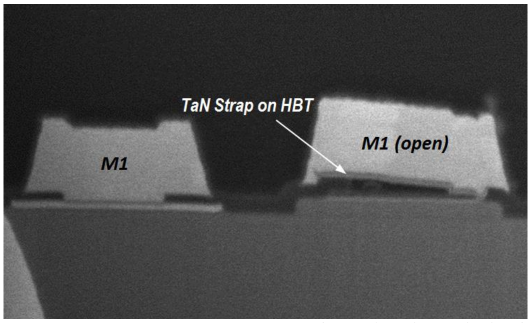

Figure 3B. Subsequent “TaN Strap” formation due to lack of resist coverage which resulted in M1 open circuits on top of HBT’s.

Approach 3: Straight Patterning of a Positive Resist

To resolve the CD control issue and resist coverage problem associated with the negative tone process, the team embarked on an approach to use a straight positive tone resist (no image reverse), which offered improvement in coat conformality over regions of high topography and also yielded superior pattern fidelity of the TaN resistors. The main issue with the negative tone resist was that it was very planarizing. Thus, every incremental increase in resist thickness in the field (bottom of topography where TaN resistors are printed), did not equate to the same thickness increase over the higher topography regions where the HBT required adequate resist coverage. Various attempts were made to improve the conformality of the negative resist but to no avail. The DOP (degree of planarization) for the negative resist was much too high and could not offer sufficient resist coverage over the HBT during the dry etch step. This is illustrated in Figures 4A and 4B where the DOP is calculated after the coating of each resist type.

$$\mathrm{DOP}\ (\%) = \frac{[d - (h_o - h)]}{d}$$

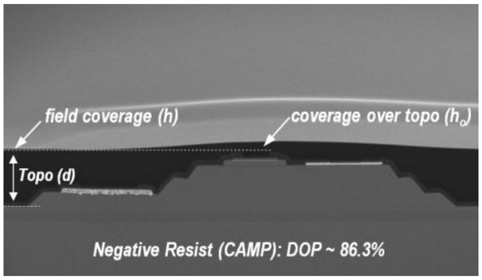

Figure 4A. Degree of planarization for negative tone resist.

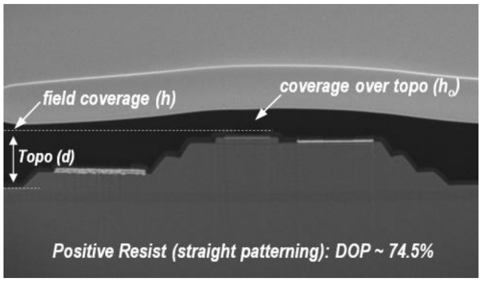

Figure 4B. Degree of planarization for positive tone resist.

The deployment of the positive tone resist scheme required a change in mask polarity (clear to dark field), but ultimately offered all of the desired photo requirements for printing robust TaN resistors. High throughput was achieved, TaN wings and HBT resist coverage yield concerns were eliminated, CD control was significantly improved, and resist solubility was much better in NMP. The positive resist process also offered improved TaN image fidelity over the negative resist since it had higher contrast. Furthermore, the positive slope of the positive resist allowed the resistor to be primarily governed by only the bottom CD of the resist. Whereas, for the negative resist, both the top and bottom CD’s of the resist opening played a role in printing the TaN resistor. This was one less variable to contend with. Also, since the negative resist was chemically amplified, the exposure dose required for printing nominal TaN CD’s was much lower and resulted in a significant amount of pullback at the bottom of the resist. This rendered much wider resistors, poorer linewidth control and image fidelity [3] which limited how closely the resistors could be spaced. Figures 5A and 5B demonstrate the two different resist profiles and their respective impact on TaN image fidelity.

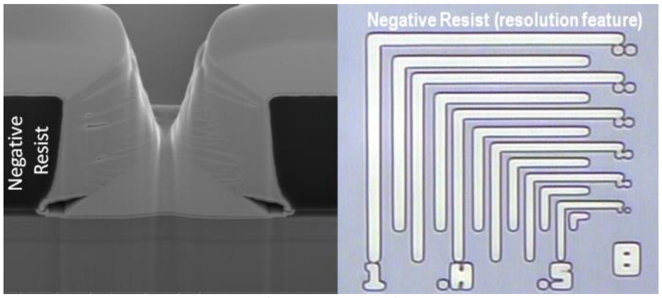

Figure 5A. Negative resist profile and image fidelity.

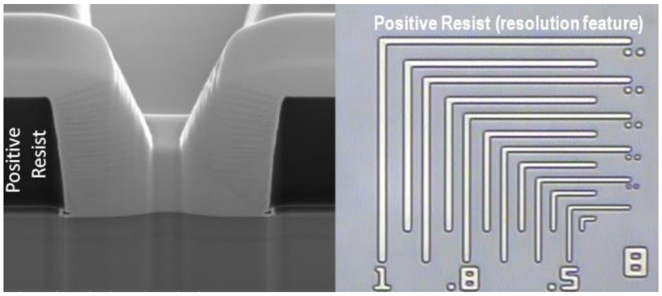

Figure 5B. Positive resist profile and image fidelity.

In addition to the advantages that came along with the straight patterning of the positive tone resist, as we developed this new approach, the team observed that there was a distinct sensitivity of TaN resistance as a function of resist thickness. It was noticed that as resist thickness increased, TaN resistance also increased. This effect has been attributed to the variable arrival angle of sputtered atoms, as compared to the straight-line arrival of evaporated atoms. The influence of resist thickness on the thickness of sputtered films has been reported by Serikawa and Sakurai [4]. As resist thickness increases, less Ta and N atoms are able to arrive at the GaAs surface and growth of the TaN film is limited. This results in a thinner TaN film and gives rise to a larger TaN resistor value. Likewise, as the resist is thinned, higher concentrations of Ta and N atoms are able to react within the resist openings. This gives rise to a thicker TaN film and thus a lower TaN resistor value. Consequently, it was found that in addition to CD control, an optimum resist thickness was also critical not only for resist profile and lift-off purposes, but also for the proper targeting of the TaN resistor itself. To further understand this phenomenon, it was necessary to evaluate TaN electrical resistance as a function of resist thickness during TaN patterning. This was carried out by running individual wafers at various cast speeds for the coating of the positive tone resist. Spin speeds ranged from 2300-3500rpm and was found to induce a +/-15% variation in TaN resistance with respect to the desired target. This correlation is illustrated in Figure 6.

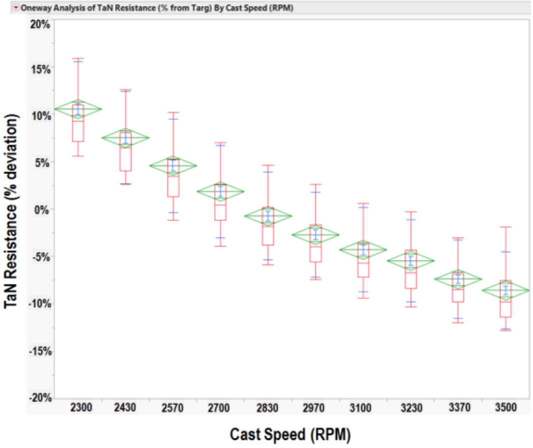

Figure 6. TaN Resistance vs. Cast Speed

Monitor wafers were also included to measure actual resist thickness for a given spin speed. It was found that resist thickness varied by as much as 4400Å across the aforementioned range in spin speeds. By plotting the linear response of TaN resistance as a function of resist thickness, we found that every 35Å of resist thickness variation equated to 1ohm of TaN resistance. This is illustrated in Figure 7.

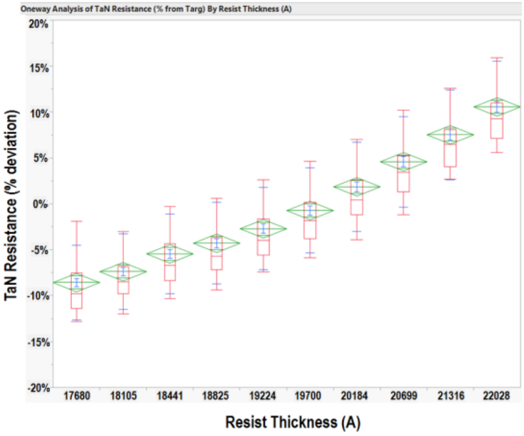

Figure 7. TaN Resistance vs. Resist Thickness

CONCLUSION

In summary, within this work we report on the many issues, challenges, and findings associated with various lithography approaches for printing TaN resistors. We have finalized on a robust photo process scheme which eventually met all of the requirements for TaN resistor process specifications.

ACKNOWLEDGEMENTS

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ACRONYMS

TaN: Tantalum Nitride
BiFET: Bipolar-and-Field Effect Transistor
BiHEMT: Bipolar-and-High Electron Mobility Transistor
HBT: Heterojunction Bipolar Transistor
CAMP: Chemically Amplified
TCR: Temperature Coefficient of Resistance
TFR: Thin Film Resistor
DNQ: Diazonaphthoquinone
CD: Critical Dimension
PEB: Post Exposure Bake
NMP: N-Methyl-2-pyrrolidone
DOP: Degree of planarization