Reducing Fluorocarbon Usage in Resistor Layer SiN$_x$ Etch

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Keywords: Silicon Nitride Etch, Global Warming Potential, Thin Film Resistors, Polymerizing Gas

Abstract

Silicon nitride (SiN$_x$) is an important and widely used material in many applications due to its intermediate (7 ~ 10) dielectric constant, ultrawide band gap, high strength, and other properties [1]. Patterning thin films of SiN$_x$ typically involves the use of plasma etching with fluorocarbons such as CF_4, CHF_3, and others [2]. While these gases are highly effective for silicon nitride (and many other) etches, they have an unfortunately high global warming potential. As a result, Skyworks Solutions has taken the initiative to substantially reduce the use of fluorocarbons and other greenhouse gases [3, 4]. In the current study, a legacy fluorocarbon-based SiN$_x$ etch for the resistor layer is investigated. This plasma etch is somewhat unique in that undercutting the dielectric beneath the photoresist mask is the desired result, and therefore little to no sidewall passivation should be required. Suitable undercut facilitates a successful liftoff of the reactively-sputtered tantalum nitride thin film. The results show that well-targeted critical dimensions and device performance can be achieved for a resistor layer etch without the use of a polymerizing gas (i.e. CHF_3). Moreover, by eliminating CHF_3, a higher etch rate is achieved and the process time can be halved without negatively impacting the device. This study demonstrates that manufacturing processes can be designed to meet or exceed both sustainability and productivity goals simultaneously.

INTRODUCTION

Greenhouses are structures in which radiant energy is transmitted through glass walls and then absorbed inside the structure, which then experiences a net thermal gain and a higher interior temperature than the surrounding environment [5]. Greenhouse gases (GHGs) act in a similar manner for planets; the planet's atmosphere is analogous to the glass walls of the greenhouse. Therefore, the composition of the atmosphere is of critical importance for the average temperature of the planet [5].

The most common GHGs generated in the United States are CO_2, CH_4, and N_2O [6]. These gases comprise nearly 97% of GHGs by weight in the U.S. The remaining 3% comprise hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), SF_6, and NF_3 [6]. These 3% have an outsize impact on global warming as their global warming potentials (GWP) range from hundreds to thousands of times that of CO_2 [7]. Moreover, the semiconductor industry is a major contributor to both the current usage of GHGs as well as to the projected growth in the use of these gases [6]. Based on these considerations, Skyworks Solutions has taken the initiative to substantially reduce the use of GHGs in manufacturing processes [3, 4].

The challenge to reduce GHGs is formidable as they are essential for many etch processes, as well as cleans for chemical vapor deposition tools and much more [2, 8]. Most studies to date have focused on alternative gases with lower GWP such as C_4F_6, C_6F_6, and others [9, 10]. While these molecules achieve lower GWP, they are not without challenges such as the fact that C_6F_6 must be heated to 130 °C to vaporize it [10]. There are also challenges such as ramping alternative gas chemistries to high volume and achieving cost competitiveness with conventional molecules such as CF_4 and CHF_3 [11].

In the current study, a SiN$_x$ etch is investigated which was historically a CF_4-based process using CHF_3 for sidewall passivation and pattern transfer from the photoresist mask. This process is a dielectric-assisted liftoff (DAL) in which the SiN$_x$ is undercut to facilitate TaN removal where not desired [12]. The primary goal of this work is to reduce the GWP of the resistor layer etch process without increasing cost or reducing manufacturing productivity. The results show that not only can GWP be reduced, but in fact cost and productivity can also be improved at the same time.

EXPERIMENTAL PROCEDURE

To improve sustainability and reduce cost, Skyworks Solutions is actively monitoring and controlling its fluorocarbon usage and is identifying opportunities for reductions. Alternative sidewall passivation chemistries are under consideration, however, implementing these gases would incur challenges mentioned in the introduction section and more such as handling, storage, and environmental regulations [6]. Therefore, it was desired to simply reduce or eliminate fluorocarbons wherever possible. The resistor layer SiN$_x$ etch was considered a suitable candidate for this purpose, because the goal of this process is to not only open the nitride but also to undercut the photoresist mask and facilitate metal liftoff.

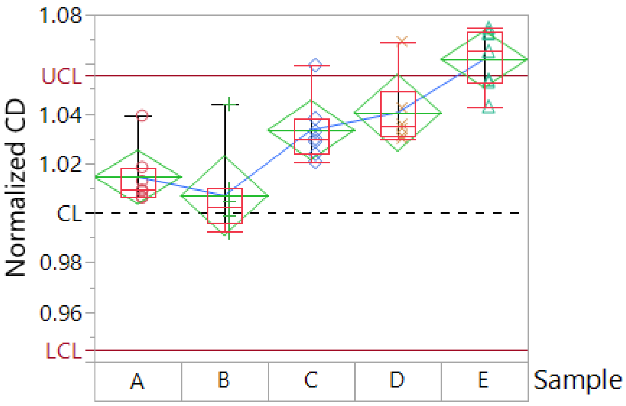

Fig. 1. Resistor layer critical dimensions for samples processed with CHF_3 (Sample A) and without CHF_3 (Samples B-E) for various etch times. Endpoint detection was activated for Sample B, and the resulting CDs are well targeted.

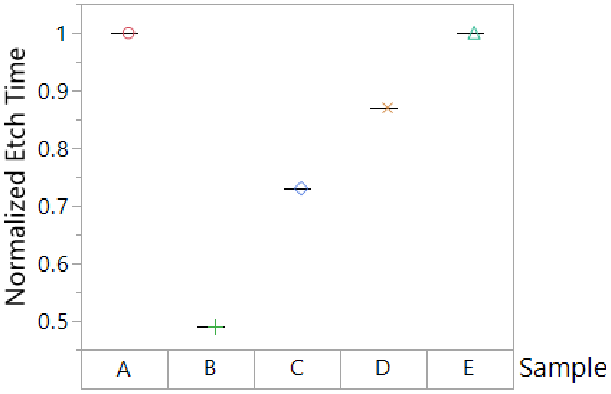

Fig. 2. Normalized etch process time for samples processed with CHF_3 (Sample A) and without CHF_3 (Samples B-E). For a similar CD, process time could be reduced by 50% for samples etched without a polymerizing gas.

Experiments using fixed etch times with and without CHF_3 were performed. These were then followed by the development of endpoint-controlled etches. Samples were characterized with inline CD measurements, cross-sectional SEM, automated optical inspections, PCM, and die probe. PCM measurements were performed both at low and at high temperatures, so that the temperature coefficients of resistance could be determined. Lastly, global warming potential of the process was calculated to quantify the improvement of the changes that were made.

RESULTS AND DISCUSSION

CD measurements (Fig. 1) indicated that SiN_x undercut doubled for the same etch time by using no CHF_3. Moreover, CDs were approximately linearly dependent on etch time (Figs. 1 and 2). Resistor dimensions not only affect electrical performance but are also critical from the standpoint of achieving healthy metal liftoff. This is because the films in this study were reactively sputtered, and sputtering is generally more isotropic than techniques such as electron-beam evaporation. Therefore, the CDs are related to SiN_x undercut and resulting TaN liftoff.

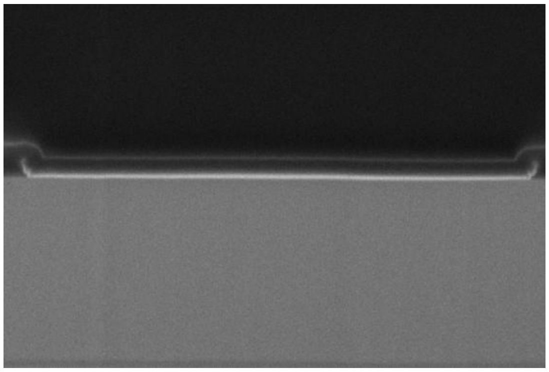

Fig. 3. SEM image of thin film resistor produced with legacy CHF_3 etch; center circuit FIB cut.

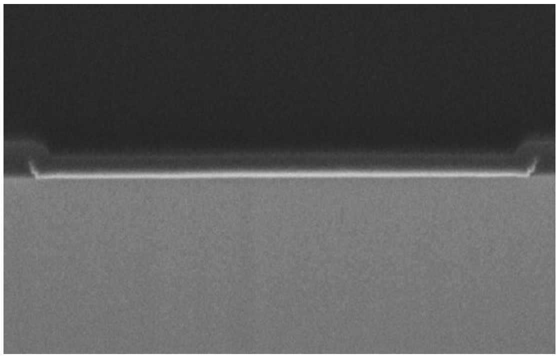

Fig. 4. SEM image of thin film resistor produced with non-CHF_3 etch; center circuit FIB cut. The TFR is practically indistinguishable from the legacy-based sample, as desired.

SEM cross sections, prepared with FIB, showed that resistors generated using suitable etch times with and without CHF_3 were nearly identical (Figs 3 and 4). This provided confidence that the general structure of these components would meet the specification requirements. Electrical characterizations were then performed. The resistance of the samples (Fig. 5) was determined to be approximately linearly correlated with the inline CDs. Cumulative probably (Fig. 6) of the resistance showed that the majority of the data was near the specification target, which indicated that high process capability was achieved.

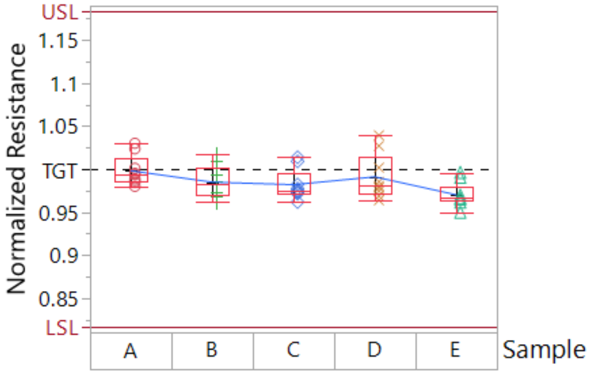

Fig. 5. Normalized thin film resistance for samples processed with and without CHF_3 for various etch times. The results show that larger CDs generally correlate to lower TaN resistance.

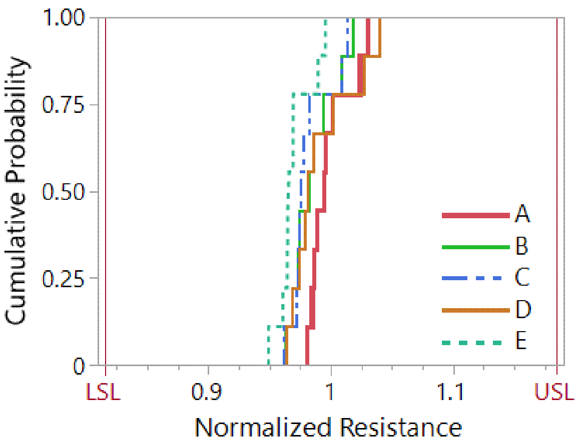

Fig. 6. Cumulative probability of TaN resistance. The data indicates that high process capability can be achieved for non-CHF_3 resistor layer etches.

One of the key deliverables for resistors is a temperature coefficient of resistance near zero [13]. Therefore, electrical resistance was measured both at low and at high temperatures (Fig. 7). The results show that CHF_3 and non-CHF_3 produced resistors are well-targeted for resistance at low temperature, and their resistance decreased slightly with temperature. Resulting TCRs were near zero, as desired.

In summary all available data indicates that CHF_3 can be eliminated from the RL etch and process time can be halved by doing so. This results in a reduction in GWP by more than 70%. The results show that it is possible to not only achieve sustainability objectives but also to improve productivity and reduce cost simultaneously.

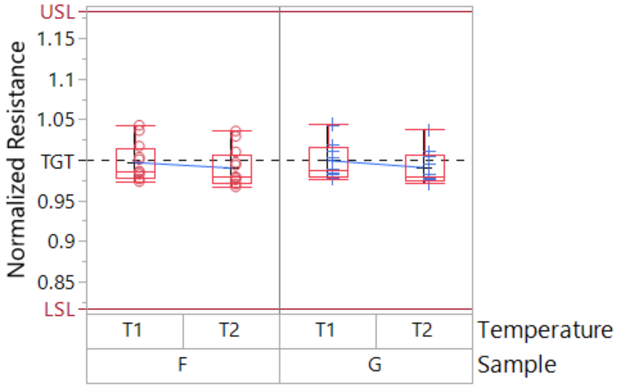

Fig. 7. Normalized resistance measured at low (T1) and high (T2) temperatures for resistors produced with CHF_3 (Sample F) and without CHF_3 (Sample G). The results show that the temperature coefficient of resistance is near zero and the samples are well matched for electrical properties.

CONCLUSIONS

In this study, a legacy fluorocarbon-based SiN_x etch for the resistor layer was investigated. This process is an ideal opportunity for reducing GWP because undercutting the dielectric beneath the PR mask is the desired result, and therefore little to no sidewall passivation is required. Suitable undercut facilitates a successful liftoff of the reactively-sputtered TaN thin film. The results show that well-targeted critical dimensions and device performance were achieved for the RL etch without the use of a polymerizing gas. Moreover, by eliminating CHF_3, a higher etch rate was achieved and the process time could be reduced by 50% without negatively impacting the device. This study demonstrates that manufacturing processes can be designed to improve sustainability, cost, and productivity simultaneously.

ACKNOWLEDGEMENTS

The authors would like to thank the photolithography and metrology teams for CD measurements and X-SEMs, as well as Ravi Ramanathan, Eric Finchem, and Ed Burke for helpful feedback on the manuscript. The authors would also like to thank George Ibrahim and team for TCR characterizations.

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ACRONYMS

AOI: Automated Optical Inspection
CD: Critical Dimensions
FIB: Focused Ion Beam
GHG: Greenhouse Gas
GWP: Global Warming Potential
PCM: Process Control Monitoring
PR: Photoresist
RL: Resistor Layer
TCR: Temperature Coefficient of Resistance
TFR: Thin Film Resistor
X-SEM: Cross-sectional Scanning Electron Microscopy