

FIB Etching of Cu with Minimal Impact on Neighboring Circuitry, including Dielectric

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1. Introduction

Addressing this challenge of editing ICs using copper interconnects is important when developing FIB circuit edit rules for designers to follow, when validating IP in a new process and when validating a proposed design ECO before a mask respin. The difficulty in FIB milling of Cu has been discussed several times [1,2] and milling non-uniformities only gets worse when a low-k dielectric is in the process [3]. The purpose of this paper is to report on success in FIB editing devices with interconnects of copper, SiO₂ and low-k dielectrics. Our approach is based on using a FIB activated chemistry to decrease decomposition of dielectric as well as bind-up redeposited copper in a non-conducting state.

Copper is not aluminum. Aluminum is a very reactive metal with a passivating oxide, protecting the aluminum from chemical attack. As a reactive, aluminum actually forms volatile compounds with several halogens (Br, Cl and I). Copper on the other hand is not very reactive nor does it form a protective passivation layer* and only in very rare instances does it form a volatile and certainly not in the non-equilibrium dynamics of ion beam impact. Its lack of reactivity however does not extend to most halogens and it is readily corroded by those chemistries, which seem best for removing aluminum—Br, Cl and I [1]. The dream of circuit edit practitioners that copper can be addressed as readily as aluminum by some "magic" chemistry is not realizable.

In a landmark paper SB Herschbein et al [1] raised awareness of the challenges to circuit edit presented by copper. Later it was revealed that the situation was even worse when low-k dielectrics were included in the interconnect stack [3] because those chemistries which offered help with copper over SiO₂ actually make the situation worse for copper over low-k. The lack of uniform etching was proven by P Russell's group at NCSU to be due to channeling [2]. Because of the great variation in sputter yield (up to 10x) with copper grain orientation [2], circuit edit requires a chemistry with copper selectivity relative to neighboring dielectrics. This selectivity can not be achieved by increasing the etch rate of copper but rather decreasing the etch rate of the dielectric. That this must

occur is unfortunate as it greatly increases circuit edit times and thereby cause circuit edit practitioners to dream of the "good old days". As copper is etched unevenly due to its strongly pronounced crystallographic grain structure, the underlying dielectric is also exposed unevenly and can be readily over-etched.

Minimal over-etch is a necessary requirement for a copper etch solution for circuit edit and especially for low-k devices. To minimize over-etching, dielectric protection ought to be a primary function of a copper-etch chemistry. On the other hand, any solution providing protection of dielectric exposed to the ion beam inevitably slows also the copper etch rate. Moreover, the highest level of dielectric protection requires the lowest current density to be employed. Therefore, the requirements of high dielectric protection and circuit-edit time-reduction are in contradiction as this paper shows.

A chemistry to enable milling uniformity during FIB removal of Cu power planes was needed so underlying dielectric would not be damaged. Cu power planes need to be removed so as to give access to lower lying circuitry. To address the need for circuit edit of copper ICs the already available FIB chemistries such as H₂O [4] and NH₄CO₃ [5] were investigated and found useful. Oxygen based chemistries release oxygen that can react with the Cu to reduce conductive redeposition as well as reorder the Cu surface so as to reduce channeling. These available FIB chemistries had been developed to address different specific circuit edit process requirements. Thus although several of these chemistries helped, a better chemistry was needed for this specific application to improve copper etching uniformity.

Several have addressed copper milling with a combination of corrosive halogens and unassisted ion etching [6,7]. However, workable their recipes might be for these practitioners, they seem too risky for the rest of us as the margin for error is very small.

The first commercial application specific chemistry for copper was NH₄OH [8], which protected SiO₂ and FSG dielectrics, presumably by continuously re-establishing any broken SiO₂ bonds. This chemistry adsorbed on the copper surface actually modified lattice constants and thus reduced channeling in the copper. Scattering effects due to NH₄OH on the surface probably does not contribute much

* CuF has been reported to be slightly passivating. Reports that F causes copper corrosion is undoubtedly due to remnants of other halogens such as Cl₂, Br₂ and I₂ within the editing tool.