Evaluating Process Parameters for Liquid Phase Electron Beam Induced Etching of Copper

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Copper interconnects continue to shrink in size due to the miniaturization of the transistor. As a consequence, circuit edit must be implemented at the nanoscale and selective copper removal techniques are essential. The current approach is to use a focused ion beam (FIB) in a gas-assisted etching process. Liquid-phase electron beam induced processing (LP-EBIP) offers an alternative approach that promises to minimize ion beam challenges such as orientation dependence, ion implantation, bubble formation, poor selectivity to dielectrics, and redeposition. LP-EBIP is a direct-write process in which an electron beam induces a chemical reaction at the interface between a substrate and bulk liquid, as shown in Figure 1, and has been primarily used for direct deposition of metals and their alloys. More recently, however, etching of silicon nitride with a liquid KOH solution was successful[1], and etching of copper with liquid reactants has also been demonstrated[2]. We validate here the selective, and site-specific, etching of a copper thin film on silicon, with aqueous sulfuric acid as the etchant.

All experiments were performed with a FEI Quanta 250 FEG environmental scanning electron microscope (ESEM). A H_2SO_4 droplet was maintained in equilibrium with the background water vapor, and the chamber pressure and substrate temperature could be used to control the H_2SO_4 concentration in solution. To better understand, and optimize, the etching process, the effects of liquid thickness, H_2SO_4 concentration, dose, and refresh time were studied. Figure 2a shows the droplet *in-situ* and preliminary etching results are presented in Figures 2b and 2c. As the liquid thickness (Figure 2b) and dose (Figure 2c) increase, the etched region becomes larger than the desired pattern. The etch resolution also improves with H_2SO_4 concentration (Figure 2b). The results suggest that copper etching with H_2SO_4 requires optimal conditions, and that a narrow operating window exists. The above-mentioned effects, and their relation to possible copper etching mechanisms, will be presented and further discussed.

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[1] E. U. Donev, C. Samantaray, M. Bresin, and J. T. Hastings, Recent Advances in Liquid Phase Electron Beam Induced Processing: Silicon Nitride Etching and Palladium Deposition (*MNE London*, 2013).

[2] M. Bresin and J. T. Hastings, Etching of copper using liquid reactants and a focused electron beam (*EIPBN Washington DC*, 2014).

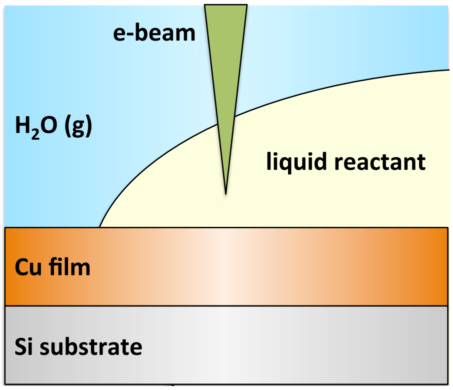

Figure 1. Schematic of LP-EBIP on a copper thin film. Depending on the composition of the liquid reactant, metal atoms can be deposited on, or removed from, the substrate.

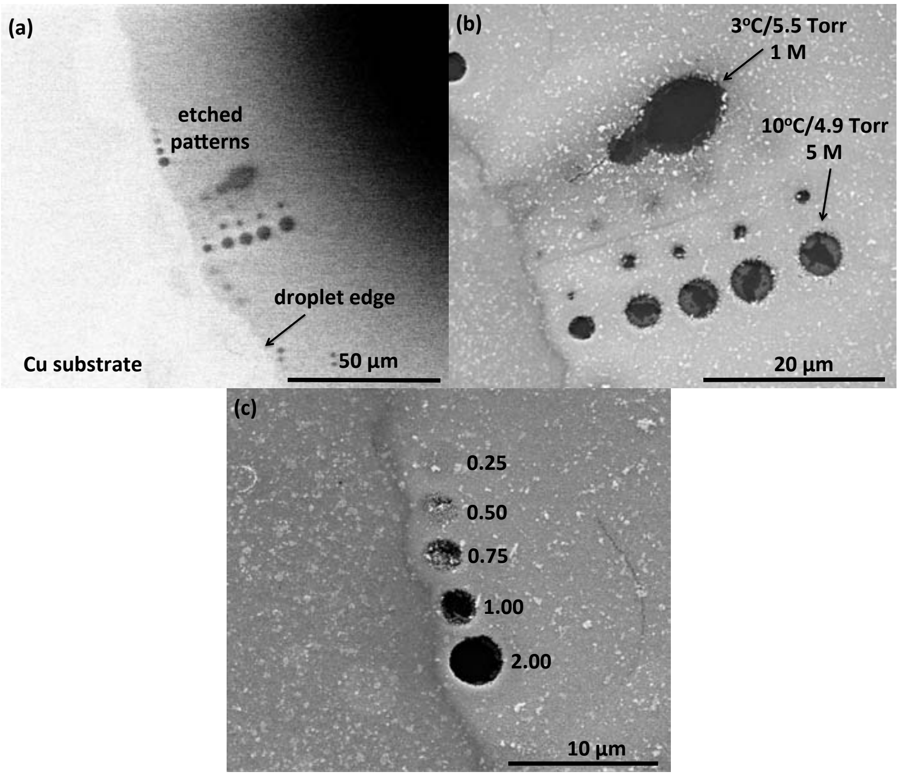

Figure 2. SEM micrographs of nominally 2-µm diameter circles etched into a ~100-nm thick copper thin film with H_2SO_4. (a) *In-situ* image of etched patterns near the droplet edge. (b) *Ex-situ* image of copper etched from the droplet edge towards its center at a dose of 1.00 C/cm^2 with 1 and 5 M H_2SO_4 (labeled). Extent of etch increases with liquid thickness and etch resolution improves with H_2SO_4 concentration. (c) *Ex-situ* image of copper etched with increasing dose from top to bottom in C/cm^2 (labeled) with 5 M H_2SO_4. Extent and depth of etch increases with dose.