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## Methods and Problems in Quantitative AES Profiling

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Quantitative Auger depth profiling is useful because of the high depth and lateral resolution, quantitative results, and rapid data acquisition capabilities. However, problems with theory, experiment, and data interpretation have hindered wider application to analytical problem solving. We illustrate the extent to which these problems have, or have not been solved, by examining materials used in semiconductor technology. Then we discuss recently developed techniques that provide more reliable Auger profile analyses.

The objective in quantitative Auger depth profiling [1] is the measurement of film composition, thickness, interface width, and other details of film geometry. We discuss three basic areas of Auger here profiling technology: theory, experiment, and data interpretation. Most major topics within these areas can be illustrated by studying just three key systems: (1) oxidized Si [2], (2) Al on oxidized Si, and (3) Ni on InP. These systems are useful to theorists who need ideal samples for testing their ideas, to workers performing Auger analysis who must align and calibrate their systems, and to those interested in learning about Auger Spectroscopy because these samples can be used to demonstrate the principles of Auger profiling. All three systems satisfy the general requirement that

they have high and low energy Auger peaks with little spectral overlap. The spread in energy provides information on escape depth effects. In addition, (1) is an excellent amorphous insulator, the oxide thickness uniformity and oxide/Si interface smoothness are the best of any known material, and the oxide composition and thickness are extremely accurately known. (2) is an example of a polycrystalline film on a flat substrate; (3) is an example of a material with slow milling rate on a material with fast milling rate -- the uses of (2) and (3) are explained below.

The first theoretical problem is the calculation of milling rates, which depend on atomic mass, ion energy, chemical environment, crystallographic direction, surface roughening and ion mixing [1,3,4]. An

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example of the crystallographic effect is the profile through an Al film -some grains mill over four times slower than others. This occurs because surface Al atoms are mobile near room temperature and the surface remains crystalline during ion milling with noble gas atoms; therefore, incoming ions channel through those grains whose crystal planes are parallel to the ion beam direction, and the mill rate for these grains is low. The theoretical basis of ion mixing and surface roughening are mostly understood [1,5]. Effects of surface roughening are illustrated here by profiling through a Ni film on InP. Both factors broaden the profile across an abrupt interface, but the area under the profile curve remains the same provided the milling rate (and a few less important factors) does not change; this area should be proportional to film thickness. Preferential sputtering and nonsteady-state situations are not yet theoretically solved [1,6,7]. These concepts of areas under profile curves, preferential sputtering, and non-steady-state conditions, are illustrated with data from very thin silicon dioxide films (about 1 nm) sandwiched between two layers of silicon.

Experimentally, the most critical initial task is system alignment. Ox-

idized Si wafers are ideal for use in focusing and aligning the ion beam, and for optimizing the ion milled crater size and shape. By balancing the electron and ion beam intensities, excellent SEM pictures of cross sections of the ion beam can be obtained using oxidized Si. Mill rates are also best determined by referencing to silicon dioxide. Mill rate tables are not yet available at the most useful energy of about 1-2 KeV; at these energies, the factors: good depth resolution, sufficient mill rate, and ease of ion beam focus and alignment are optimized. The most commonly available ion guns are of three types: back-fill type, differentially pumped, and duo-plasmatron, in increasing degree of complexity. The duoplasmatron is the most useful; the advantages include: faster mill rate, smaller crater, larger choice of gases, better beam position stability, and larger range of ion energies, compared to the other two types of ion guns. The small crater size permits accurate mill rate measurements using a surface profilometer. A disadvantage is that under certain conditions, the beam position and intensity are unstable. Among the sputtering gases, neon is the best because it is a noble gas (it does not react with the surface or contaminate the vacuum system), is pumped efficiently by ion

pumps (unlike all heavier noble gases), and permits the analysis of argon in films sputter deposited or sputter cleaned with argon. Reactive gases such as nitrogen [8] and oxygen can be used to reduce surface roughening for obtaining sharper interface profiles. This effect is demonstrated by profiling through a Ni/InP interface using argon, or using nitrogen.

Data interpretation is complicated by the fact that local film thickness variations, atomic interdiffusion, ion mixing, surface roughening, and system misalignment can all broaden an interface profile, beyond the ideal value determined by the electron escape depth and interface compositional variations. Quantitation is complicated by the fact that the area under the profile curve depends on ion mixing, preferential sputtering, surface roughening, and the mill rate.

Once the above factors affecting interface profile broadening and quantitation are identified, their effects be determined quantitatively. must The amount of ion mixing can be changed by changing the ion energy. Interface broadening due to surface roughening can be tested using nitrogen instead of noble gas milling, or by directly imaging the roughening using the SEM. Preferential sputtering can be evaluated using standards with known compositions, or by comparison with other, more quantitative techniques, such as RBS. The absolute mill rate at all points along a profile can be determined, but the procedures are somewhat involved [1]. When there is no way to quantify a particular effect using the Auger apparatus, then other complementary techniques, such as the SEM, TEM, RBS, and SIMS, must be considered. In conclusion, we have identified most of the problems associated with quantitative Auger depth profiling and enumerated some solutions that greatly enhance the reliability of profiling analyses.

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