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Research paper

Design, fabrication, and testing of surface acoustic wave devices for semiconductor cleaning applications

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ABSTRACT

Numerous cleaning steps are utilized in the production of IC's in semiconductor facilities, involving the consumption of considerable amounts of energy and chemical cleaning agents. Sonication of surfaces containing particulate defects is one of the cleaning methods used to enhance particulate removal and increase device yield. The mechanisms of action achieving this particle removal are generally considered to involve contributions from two physical phenomena: 1) acoustic cavitation and 2) acoustic streaming. In efforts to reduce damaging effects of sonication, while enhancing the ability to remove particles of decreasing sizes, semiconductor tool manufactures have historically increased the operating frequencies moving from ultrasonics, characterized by frequencies in the kHz range, to megasonics, with frequencies in the low MHz range. This work focuses on the development of various MEMS acoustic transducers designed for efficient operation at frequencies in the hundreds of MHz. Design, fabrication, and results of testing exploring the ability of these devices to remove nano-scale particles is presented and discussed.

1. Introduction

The continued scaling of semiconductor devices presents a number of engineering challenges which must be overcome in order to maintain historic yield and cost/performance trends. Among these broad challenges; those related to surface conditions and cleanliness are particularly relevant for yield. For example, the ITRS points out the need to remove particles of continually decreasing sizes, or critical diameter, as a challenge requiring innovative solutions [1]. The critical diameters of these contaminant particles is now approaching 10–20 nm, and the challenge of removing these particles is increased by additional constraints preventing etching of the underlying surface and limiting damage to increasingly sensitive structures.

The balance between physical and chemical aspects of cleans processes is increasingly critical, and the need for more precise control of both is evident. The introduction of physical forces to remove a particle can be achieved by a number of techniques depending on particle size and other considerations, and can include: brush scrubbing, spray cleaning, laser cleaning, sonication, etc. Techniques involving the utilization of physical forces, described above, now require more precision as the structures present on wafers are becoming ever more susceptible to damage; current research is focused on better understanding and controlling such forces to prevent these damaging effects [2].

This work has focused on the utilization of sonication methods operating at frequencies hundreds of MHz, nearly two orders of magnitude greater than the frequency utilized by current megasonic tools. Ultrasonic cleaning emerged in the 1950s, operating at frequencies around 20–40 kHz [3]. By the 1970s a megasonic technique operating in the range of 850–900 kHz had been developed at RCA, whereby smaller particles were able to be removed at lower power densities relative to ultrasonic systems [4]. Improvements in this approach allowed it to remain the preferred physical removal method until around the mid-2000s, when the lack of precise control over the cavitation-based technique became a more significant problem [2,4]. In this article, the potential impact of a further increase in operational frequency is investigated, especially with regards to the physical mechanisms of particle removal.

2. Material and methods

A combination of simulation and experiment, in addition to an approximate theoretical formalism, was used to analyze the ability of this technique to expose surface contaminant particles to the forces necessary to achieve removal. FEM simulations were developed to establish a preliminary understanding of the effects of certain parameters. Fig. 1 illustrates those parameters initially investigated for impact on streaming velocities, such as, the radius of the device, applied voltage, and distance or height, from the surface to be cleaned. The acoustic wave is generated by application of an AC signal to every other electrode of an interdigital transducer (IDT) patterned on a piezoelectric material, in this case 128° Y-Cut LiNbO3. The resonant frequency is determined by $f = v_{SAW}/2p$, where v_{SAW} is the velocity of the surface acoustic wave (SAW), a property of the material, and p is period, or center-to-center

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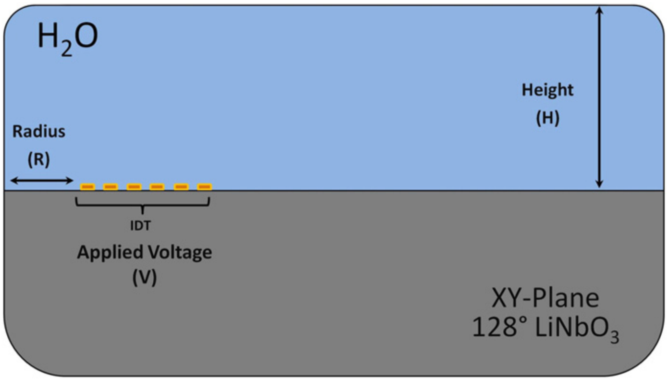

Fig. 1. Illustration of the geometry of the FEM simulations performed with primary parameters under investigation, radius, height, and voltage, labeled on image. The simulations were performed for 128° $LiNbO_3$, the material used for fabrication of devices.

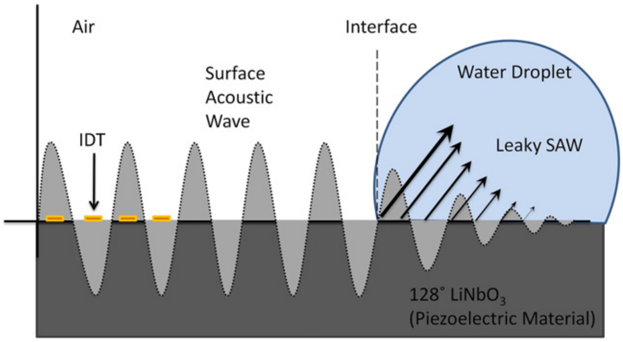

Fig. 3. Illustration of acoustic streaming. A surface acoustic wave (SAW) is shown propagating away from a set of IDTs into a region with a droplet on the surface. The wave then leaks into the liquid, at which point it attenuates in the liquid, resulting in acoustic streaming.

distance between adjacent fingers of the IDT, so that λ, or wavelength of the SAW, is equal to 2p. The computational modeling of acoustic streaming is achieved by simulating the mechanical action of the piezoelectric material at the resonant frequency while in contact with the fluid medium. A body force acting in the liquid is then introduced, proportional to the resultant acoustic intensity field, given by $F = \beta I/c$, where β is an attenuation coefficient, I is the average acoustic field intensity, and c is the velocity of the acoustic wave in the liquid [5].

The authors of [6–8] demonstrated and discussed an effective cleaning process window, utilizing lateral force AFM measurements, of relatively consistent range for applied forces required to break patterns, and also remove particles, of decreasing sizes. A prerequisite for working within this window is the ability to tune the forces and precisely direct them on the surface. To determine the streaming velocities generated by the SAW devices fabricated for this study, particle velocimetry was utilized with ~9 μm PSL particles as tracers. Using a high-frame rate microscope setup, the devices were immersed in DI water and seeded with the tracers; video was obtained of the devices under operation with still frames shown in Fig. 2. This information may be used to approximate streaming near the focal region over several frames, by $v = \frac{F_{rate} \times d}{F_{number}}$, where F_{rate} is frame rate during video capture, F_{number} is number of frames passed for a given particle motion, and d is displacement of the particle in that time frame.

By characterizing various device designs for streaming velocities, it was possible to determine those which were able to generate the highest velocities. Initial particle removal experiments were then conducted with one of these top performing SAW devices. The die onto which the particles were deposited had regions of Si as well as patterned regions with 65 nm SiO_2 lines. A solution of 50 nm PSL particles was mixed with DI H_2O and the die was dipped face down into it. It was then allowed to dry for approximately 10 min. This approach was used to achieve a deliberately high density particle distribution, necessitated by the fact that SEM inspection was being used, and two regions, exposed and unexposed to the acoustic transducer, were being compared. Brems et al. discuss the use of high density distributions under similar rationale [8]. Upon allowing the particles to dry onto the surface the die was cleaved in half, one half to remain unexposed, and the other to be exposed. The regions inspected by SEM were directly adjacent to the cleave line. For the exposed half of the die the cumulative operation time was nearly 5 min, under a range of substrate to device distances of 100–500 μm, at 328 MHz with an applied power of approximately 44 dBm. The operation time was relatively long owing to the manual manipulation necessary to position the devices using this setup.

The SAW devices were fabricated in SUNY Polytechnic's 200 mm cleanroom facility. A 4″ wafer of 128° Y-Cut $LiNbO_3$ was used in a liftoff process to pattern the IDTs. Various metals have been explored; in the devices discussed metallization was achieved by RF magnetron sputtering of W or *e*-beam deposition of Au. The metallization ratio, $MR = w_{IDT}/p$, where w_{IDT} is the width of one IDT finger, was designed to be 0.5 for all cases, though slight process variability may introduce

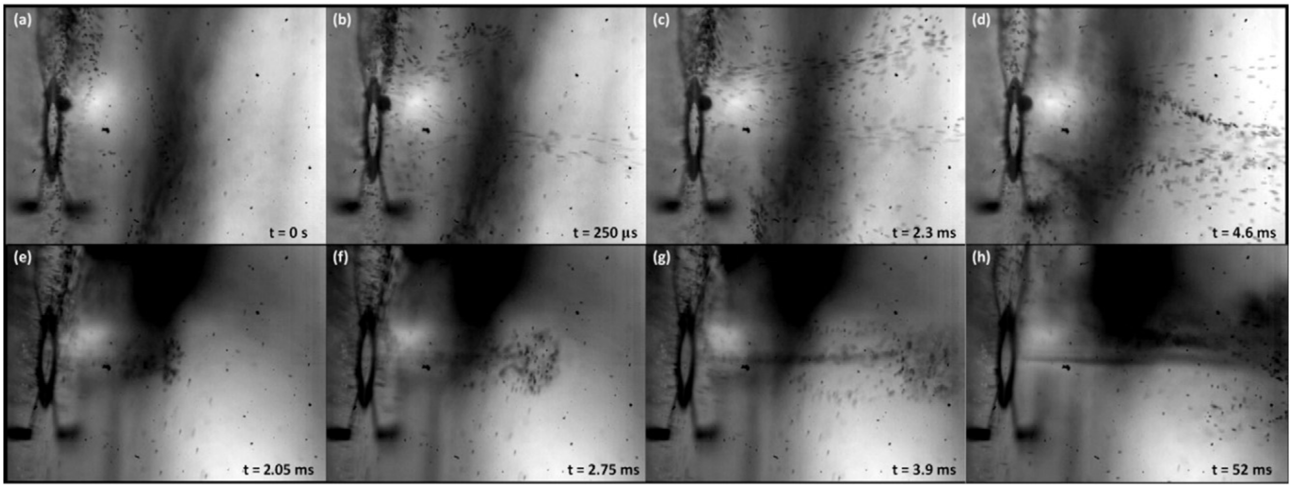

Fig. 2. Images captured via high speed camera. PSL particles enable visualization and quantification of the acoustic streaming flow field in the first moments after activating the device. (a–d) shows operation at 329 MHz, and (e–h) at 530 MHz.