

Numerical Analysis of Ultra-High Frequency Wire Bonding

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Abstract

For commercial applications, it is assumed the evolution of ultrasonic wire bonding process frequencies will progress from the currently used frequency ranges to higher frequency ranges. A finite element frequency analysis is reported for a typical ball bonding application. This analysis is extended to ultrasonic frequencies between 1 and 700 kHz. Based on simulations, the next higher range suitable for industrial wire bonding is suggested to be between 390 and 410 kHz. In this range, the process is more sensitive to the capillary geometry. Between 27% and 76% less ultrasonic horn amplitude is required for successful bonding, depending on the capillary type used. Underpad stress is found smaller. The suggested frequency range has the potential to improve the low stress, low temperature, and low bond time performance of the bonding process. The results serve as guidelines for future designs of ultra-high frequency transducers, capillaries, and bonding processes.

Keywords: ultrasound, wire bonding, finite elements, design

Introduction

Microelectronic Wire Bonding is an ultrasonic microwelding process used to interconnect integrated circuits with substrates using fine wires [1]. While the bond connection of existing processes are reliable, advanced chip and substrate designs and materials are pushing the limits of these processes. One challenge is the need to bond with less mechanical stress to avoid the development of cracks or delamination in the chip. This is important for chips with low-k dielectrics, pads over active circuitry, or for bonding with Cu instead of Au wire due to the higher hardness of Cu. Another challenge is successful bonding with lower ultrasound irradiation times to increase throughput. A third challenge is bonding at reduced process temperatures as required to maintain the structural integrity of polymer substrates.

All these challenges were successfully addressed when the industry moved from the classical 60 kHz ultrasonic transducers to higher frequency transducers operating in the 120 to 140 kHz range. The move has lead to higher bond quality at lower process temperatures (e.g. 160°C) and enabled reliable bonding on many organic substrates, e.g. ball grid arrays. The higher frequency further lead to the reduction of bondtime from about 25 ms down to 8 to 12 ms.

Increasing the ultrasonic frequency further up to the next level is expected to be even more beneficial. This contribution predicts this next level using a harmonic frequency response finite element model. The model is applied to describe the effect ultrasonic frequency has on some mechanical aspects of the bonding process with a set of typical capillary tools used by the industry.

Finite Element Model

The 3D geometry used includes the capillary portion protruding from the ultrasonic horn, the bonded ball, pad, chip, and die attach adhesive. The capillary is suitable for an 80 µm bond pad pitch process. This geometry does neither include the ultrasonic horn, nor the transducer, nor the capillary portion clamped by the transducer. The model and all its boundary conditions correspond to an experiment [2] with 130 kHz ultrasonic frequency, and are described in detail in [3]. Only a summary of the model is given in this subsection. The software COMSOL 3.4 is used.

In wire bonding, the end of the process is characterized by the ball bonded firmly to the metallization. In this state, the mechanical stresses on the ball and chip are expected to be largest. Therefore, only this state is simulated with the ultrasonic irradiation.

tion. A frequency analysis is used with these simplifying assumptions:

1. No plastic deformation.
2. No thermal effects.
3. No interfacial friction.
4. Intermetallic growth is ignored.
5. Effects of air-damping on vibration are negligible.

The ultrasonic vibration is applied in y -direction and is assumed symmetrical with respect to x . Therefore, only the $x \geq 0$ half of the geometry is modelled for simplicity. The z -direction is the main capillary direction and perpendicular to the chip surface.

Geometry parameters are given in Table 1 and are illustrated in Figs. 1 (a)-(c). An octahedral pad structure is used consisting of a metallization layer that is embedded in a typical CMOS dielectric layer stack treated here as one uniform component (dielectric). The mesh is shown in Figs. 2 and 3 for the whole geometry and the ball bond detail, respectively. Maximum mesh element sizes down to $0.2 \mu\text{m}$ are set for several lines of interest in the ball bond region. All other regions are meshed more coarsely. The mesh elements are tetrahedral and their total number is 90,713.

The material parameters used are given in Table 2. The Si chip is simplified as an isotropic component. The loss factor (or internal friction Q^{-1} [4]) for viscous damping in alumina is estimated from [5, 6] to be $\eta = 2 \times 10^{-4}$. It is used for all simulations and applied to the components other than the capillary, too.

The top surface area (TSA) of the capillary part is where the ultrasonic displacement of $A_{US} = 0.559 \mu\text{m}$ is applied [2]. The bottom of the adhesive layer is kept fixed. A horn nodding effect [3] is approximated by ultrasonic displacement conditions $+\delta_z$ and $-\delta_z$ at lines at $x = 0$ on TSA in $+y$ and $-y$ directions, respectively, where $\delta_z = \tan(\epsilon) \times (TD - TID) \times 0.25$, and TD and TID are from Table 1. To stabilize the model, the line $y = 0$ on TSA is held fixed in z -direction. The value $\delta_z = 13.896 \text{ nm}$ is used [3], resulting in a simulated ultrasonic force amplitude acting tangentially on the pad,

$$F_{US}^{\text{sim}} = \int \tau_{yz}^{\text{US}} dIFA = 0.251 \text{ N}, \quad (1)$$

where τ_{yz}^{US} is the only US stress component contributing to F_{US} , and the integration is carried out over the interfacial area (IFA). This value corresponds well with the experimental value [2],

$$F_{US}^{\text{exp}} = 0.258 \pm 0.016 \text{ N} \quad (2)$$

Example Result

Figs. 4 (a) and (b) show the state of maximum deformation during the ultrasonic cycle for the whole model (scale factor 200) and the bonded ball detail (scale factor 50), respectively. The effect of the normal force F_N required for successful bonding is excluded in these results.

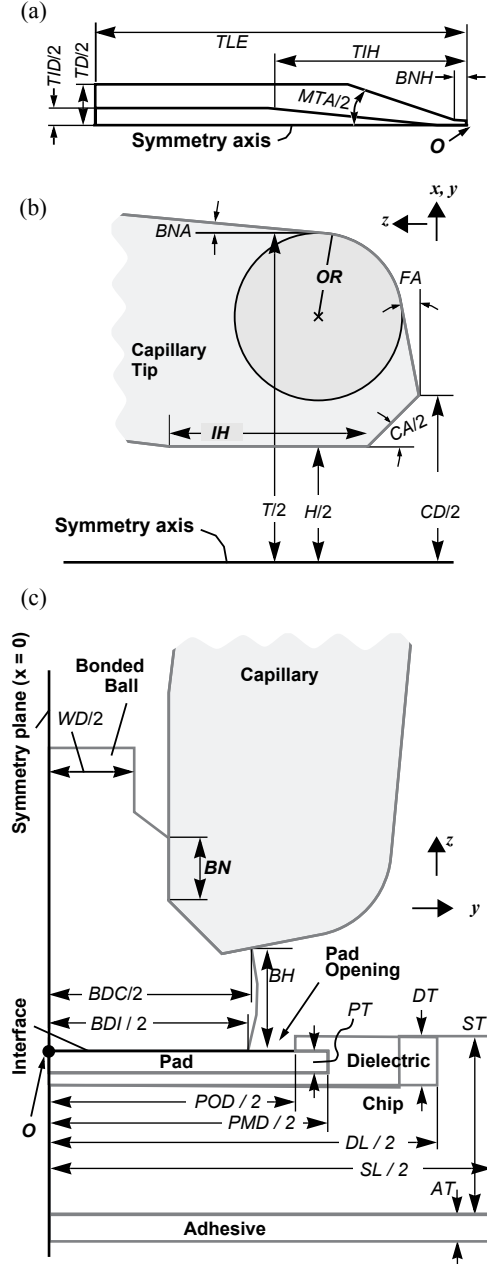


Figure 1 : Layout of model with parameter definitions (cf. [3]). Only half of geometry shown (for symmetry). (a) Capillary tool, (b) tip detail, (c) ball bond detail. Not to scale.

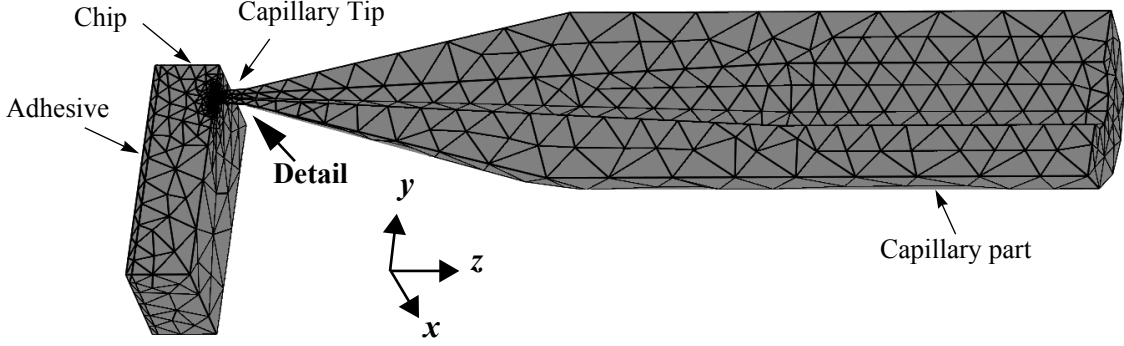


Figure 2 : Example mesh of model (cf. [3]). Only half of entire geometry is modelled due to symmetry. Only part of capillary is modelled.

The capillary tip is inclined by $\approx 0.12^\circ$ with respect to the z direction. This capillary tip inclination changes the uniformity of the interfacial σ_z stress produced by the bonding force ("inclination effect"). While the experimental F_N provides a mainly constant σ_z^N at the interface, the inclination oscillation adds an ultrasonically oscillating component σ_z^{US} .

Table 1: FE model geometry values for tool, ball, chip with pad structure, and adhesive

Quantity	Variable	Value
bottle neck angle	BNA [°]	10
bottle neck height	BNH [μm]	275
chamfer angle	CA [°]	90
chamfer diameter	CD [μm]	50
face angle	FA [°]	11
hole diameter	H [μm]	35
inner height	IH [μm]	42
outside radius	OR [μm]	12
tool outer diameter	TD [μm]	1587
tool inner diameter	TID [μm]	600
tool inner height	TIH [μm]	4875
tool length extending	TLE [μm]	7600
tool main taper angle	MTA [°]	30
ball $\varnothing$ at capillary	BDC [μm]	59.4
ball $\varnothing$ at interface	BDI [μm]	58
ball height	BH [μm]	16.3
ball neck height	BN [μm]	10
adhesive thickness	AT [μm]	50
silicon length	SL [μm]	2000
silicon thickness	ST [μm]	500
wire diameter	WD [μm]	25
pad thickness	PT [μm]	2
pad opening $\varnothing$ (min.)	POD [μm]	70
pad metalliz. $\varnothing$ (min.)	PMD [μm]	75
dielectric thickness	DT [μm]	4
dielectric layer length	DL [μm]	150

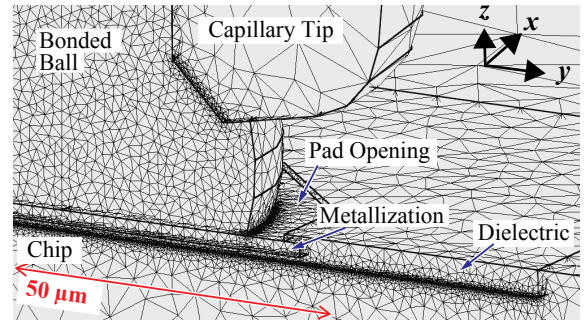


Figure 3 : Mesh detail including ball bond portion of model (cf. [3]).

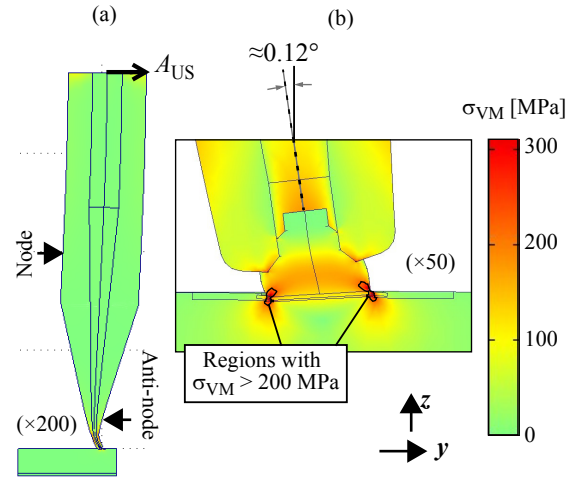


Figure 4 : Example model from [3]. Ultrasonic von Mises stress σ_{VM} and deformation required for $F_{US} = 258 \text{ mN}$. (a) Whole model. (b) Bonded ball detail. Bond force is excluded. Deformation scale given in parantheses.

Thus, $\sigma_z = \sigma_z^N + \sigma_z^{US}$. The inclination oscillation might cause tensile values of σ_z to exist during a fraction of an ultrasonic cycle at the side opposite to the

momentary US direction of the capillary tip. Most of this tensile σ_z^{US} stress is compensated in the real bonding process by the compressive σ_z^{N} , but an area with $\sigma_z > 0$ can remain (Fig. 5). The inclination oscillation is recommended to be below a certain limit for practical applications. The tensile σ_z initially can produce tiny, oscillating gaps on the +y and -y sides in the beginning of real bonding illustrated in Fig. 6 (a). At an advanced bonding state, this gap disappears once bonding is strong and another gap can form at the capillary chamfer as shown in Fig. 6 (b).

Variation of Frequency

In addition to the presented model with MTA = 30°, a model with MTA = 20°, and a model with MTA = 50° are generated. Capillaries with these values for their main taper angle are commonly used in industry. The three models are termed MTA20, MTA30, and MTA50. To speed up the calculations at various frequencies, the originally fine mesh was coarsened, e.g., down to 8944 elements for the

MTA30 model. While having a major effect on the smoothness of stress fields, this coarsening produces only a minute change of the F_{US} results presented here.

Values of F_{US} are evaluated from simulations of the three example capillary geometries, and an overview of the result is given in Fig. 7. The ultrasonic boundary condition produces lateral vibration. The first three resonances in lateral direction are found for each of the capillaries and summarized in Table 3.

Analysing F_{US} in the range of presently used ultrasonic frequencies (i.e. 130 to 140 kHz) [range 1, see Fig. 7] shows that for all three capillary types, F_{US} is relatively flat, resulting in ultrasonic behavior that is robust enough for industrial application. Range 1 is roughly $\Delta f = 75$ kHz higher than the first set of resonances. The second set of resonances is found at 305, 295, and 257 kHz for the 20°, 30°, and 50° type capillaries, respectively. A second range (range 2) where F_{US} is relatively flat is estimated between 380 and 420 kHz (Fig. 8), which is about $\Delta f = 100$ kHz higher than the 2nd set of resonances.

When comparing an example operating frequency in each of the two specified ranges, a parameter to look at is the ultrasonic amplitude A_{US} required at the horn to achieve an ultrasonic tangential force as given in Eq. 2 (258 mN) which is an experimentally obtained value. These amplitudes are evaluated and

Table 2: Material parameters [2, 3]

Component	Material	E [GPa]	ρ [kg m ⁻³]	ν [-]
bonded ball	Au	77.2	19290	0.424
pad	Al	70	2700	0.35
dielectric	SiO ₂	70	2200	0.17
adhesive	Epoxy	5	920	0.33
chip	Si	170	2329	0.28
capillary	Al ₂ O ₃	389	3552	0.25

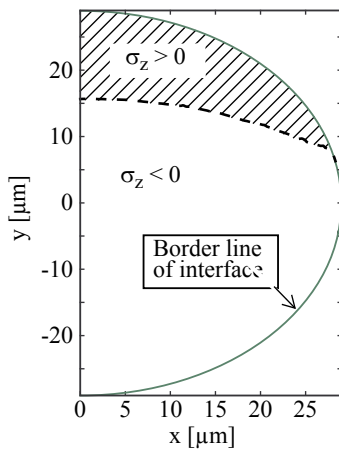


Figure 5 : Stress component σ_z at location under IFA ($z = -0.1 \mu\text{m}$). Top view. Cross hatch indicates tensile zone.

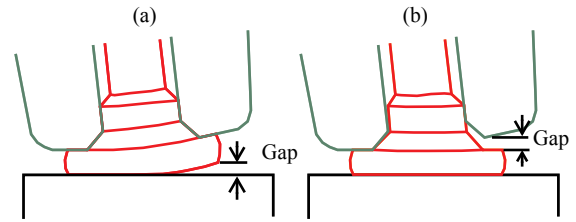


Figure 6 : Illustrations of gaps occurring during ball bonding. (a) At interface before bond completion. (b) At interface between capillary tip and bonded ball, after bond completion. Not to scale.

Table 3: Lateral Resonance Frequencies of Capillaries

MTA	Lateral Resonances [kHz]		
	1st	2nd	3rd
20°	72	305	556
30°	61	295	646
50°	50	257	632

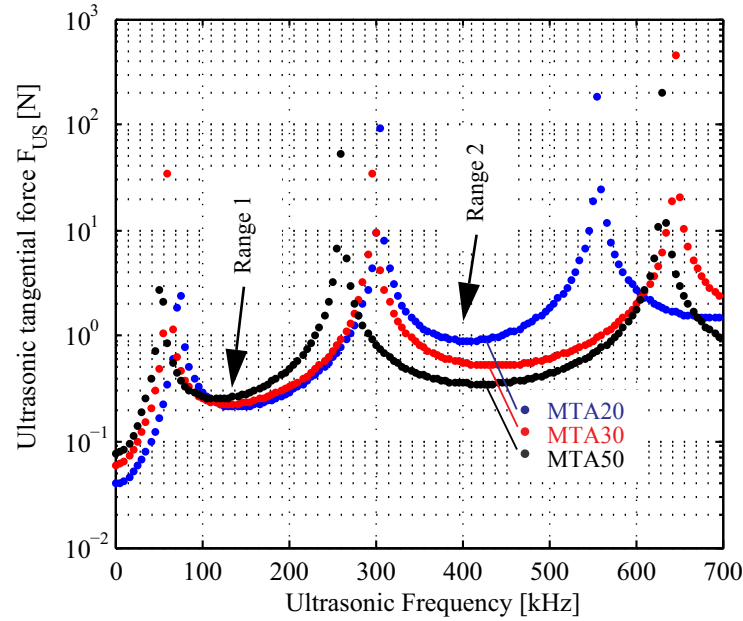


Figure 7 : Ultrasonic force on bondpad: frequency response for three capillary types. $A_H = 559$ nm.

given in Table 4. The higher operating frequency results in required amplitudes that are between 27% (MTA50) and 76% (MTA20) lower in these models.

In range 2, an example operating frequency of 400 kHz is chosen and the stress fields $\sigma_{400\text{kHz}}$ under the pad are calculated (Fig. 9) and compared with those obtained with an operating frequency of 130 kHz ($\sigma_{130\text{kHz}}$) as shown in Fig. 10. The differences observed are up to 6% with the higher fre-

quency producing lower stress levels. Therefore, increasing the operating frequency does not increase the stress in the chip during bonding. Neither does it increase the inclination effect, and so the bonding force parameter can be chosen similarly for both frequencies.

Conclusions

An ultra-high frequency range is found by numerical simulation and predicted to be suitable for wire bonding with typical capillary geometries currently used in industry. In this range, substantially less horn amplitude is required to achieve the desired shear strength, but the required amplitude varies stronger with capillary type than in the currently used range.

It is suggested that future ultra-high frequency ultrasonic transducer designs have robust resonances in the suggested range around 400 kHz to

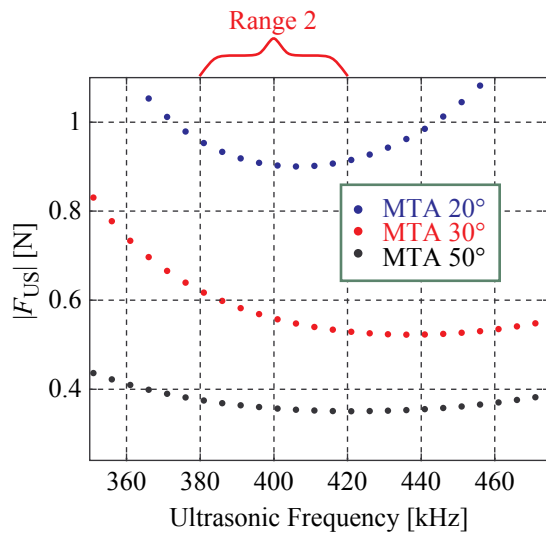


Figure 8 : Simulated ultrasonic tangential force in range 2 for three types of capillaries. $A_{US} = 559$ nm.

Table 4: Amplitudes A_{US} [nm] that are Required for Successful Bond (with $F_{US} = 258$ mN).

Frequency	Main Taper Angle		
	20°	30°	50°
130	642 nm	565 nm	497 nm
400	154 nm	229 nm	363 nm
reduction	-76%	-59%	-27%

achieve shorter bonding times and higher bondability at lower temperatures and with lower cost materials.

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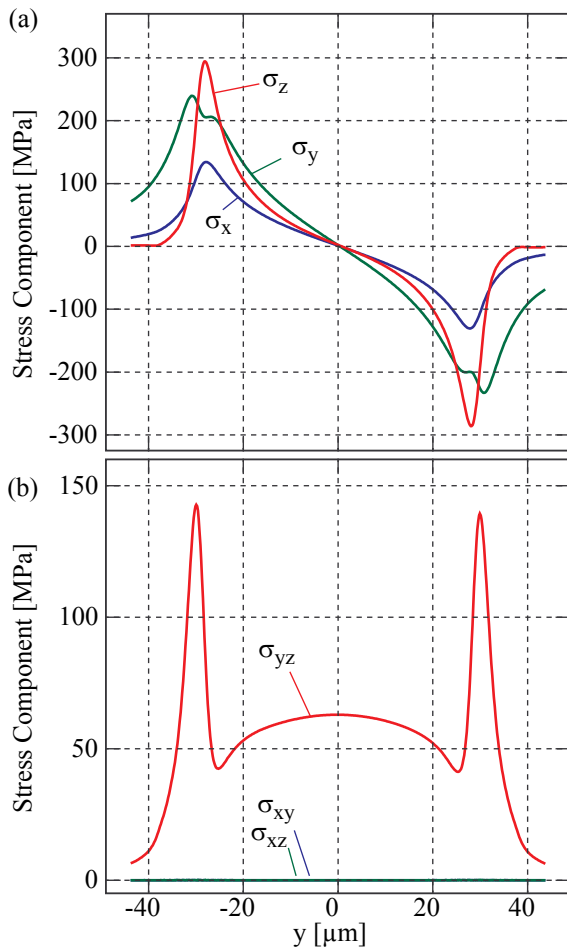


Figure 9 : Simulated stress components along $x = 0$, $z = -100$ nm below interface, $f = 400$ kHz, and $A_{US} = 0.599$ μm . (a) Normal, (b) shear stress components. Fine mesh.

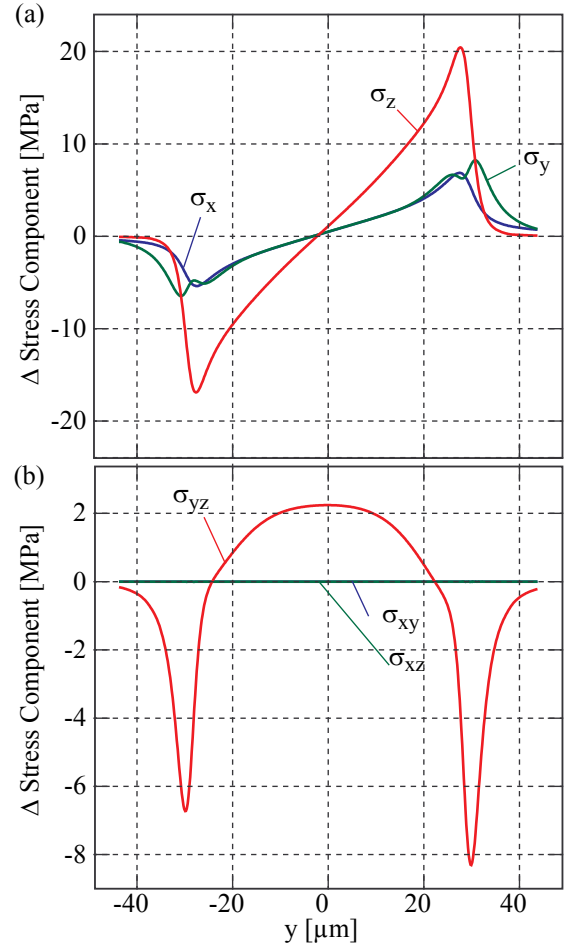


Figure 10 : Difference $\sigma_{400\text{kHz}} - \sigma_{130\text{kHz}}$ stress components along $x = 0$, $z = -100$ nm below interface, $f = 400$ kHz, and $A_{US} = 0.599$ μm . (a) Normal, (b) shear stress components. Fine mesh.

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