

NUMERICAL MODELLING OF PLUME EXPANSION AND MOTION OF DROPLETS OF ABLATED MATERIAL IN A CAVITY DURING LASER DRILLING OF SILICON WAFER



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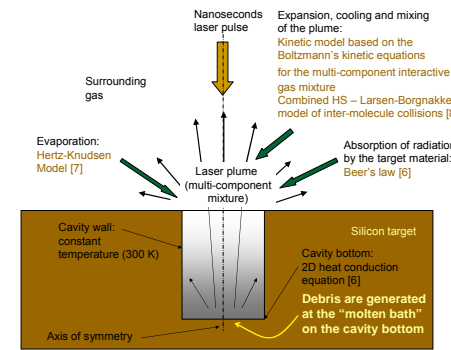
Introduction

- The efficiency of deep drilling and micromachining of materials by laser pulses depends significantly on the aspect ratio (depth/width) of the machined slot or cavity. If the aspect ratio increases the efficiency (ablation rate) drops due to re-deposition of ablated material at the cavity walls. At moderate laser intensities, a significant part of ablated material is removed from the surface in the form of liquid droplets [1]. At the same time the plume expansion is studied mostly for the plane irradiated targets [1-5] and the behavior of liquid droplets is not studied yet theoretically.
- The purpose of this work is to study numerically the expansion of the laser plume generated by the single nanosecond laser pulse irradiating the bottom of the cylindrical cavity at the silicon target and the subsequent motion of submicron debris generated in the vicinity of the laser spot where the silicon is molten.
- Submicron silicon debris are introduced into the pre-calculated, non-stationary, fields near the laser spot. Their trajectories are tracked, taking into account gravity and drag forces, heat exchange and evaporation/condensation on their surfaces.

Cases under consideration

- Laser pulse:** Third harmonic solid state laser, wavelength 355 nm
 Gaussian profile in time and for radial distance
 Pulse duration (FWHM): 23 ns
 Spot diameter (FWHM): 25 μm
 Pulse energy: 30.6 μJ
- Target material:** Silicon. Its thermal and optical properties – see [1,9-12]
- Cavity:** Aspect ratio (height/diameter) 1 – 4
 Diameter 75 μm
- Surrounding gas:** Air/gas mixture
 Initial pressure: 0.1 – 1 bar
 Initial temperature: 300 K
- Debris:** Spherical droplets or solid particles of silicon
 Initial particle radius 0.1 – 1 μm
 Initial velocity at the irradiated surface 0 – 100 m/s

Mathematical model and numerical algorithm



Problem is solved in 2D axisymmetric geometry
 Melting of the target and change of its shape due to evaporation/condensation are taken into account
 Finite-volume method of the second order for the thermal model of the target
 NTC scheme [8] by Bird of the Direct Simulation Monte Carlo method:
 > Parallelization based on the domain decomposition method and MPI library
 > Adaptive grid refinement

Model of debris motion and heat and mass transfer

Debris motion equations

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i$$

$$m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{F}_{drag} + \mathbf{F}_{gravity}$$

$$m_i C_{Si} \frac{dT_i}{dt} = Q_{convection} + H_i \psi_{evaporation}$$

$$\frac{dm_i}{dt} = \psi_{evaporation}$$

Initial conditions at the irradiated surface

$$v_{ix} = V_0, \quad v_{iy} = 0$$

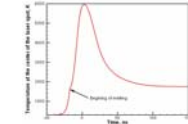
$$T_i = T_0$$

$$m_i = \frac{4}{3} \pi r_0^3 \rho_0^3$$

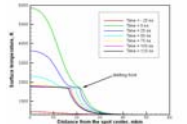
Initial debris velocity V_0 and radius r_0 are parameters of the model.
 Sub-micron debris move in the plume in transitional flow regime.
 To determine \mathbf{F}_{drag} , $Q_{convection}$ and $\psi_{evaporation}$ models from [13], [14] and [7] are used.

Temperature of the bottom surface of the cavity

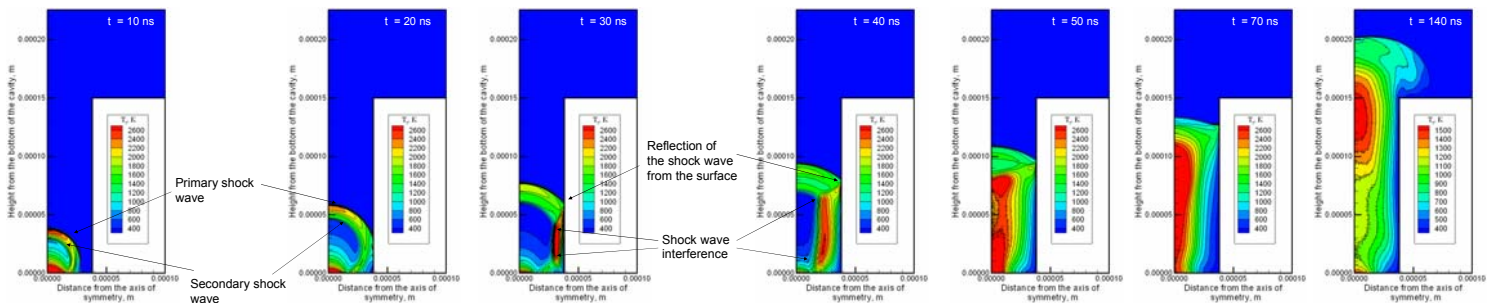
Temperature at the center of the laser spot



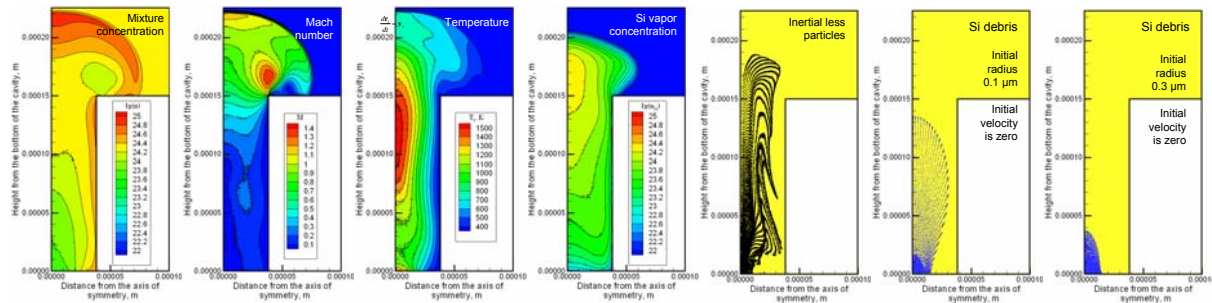
Temperature distribution along the target surface



Plume expansion (mixture temperature fields) into air at 0.1 bar, cavity aspect ratio is equal to 2

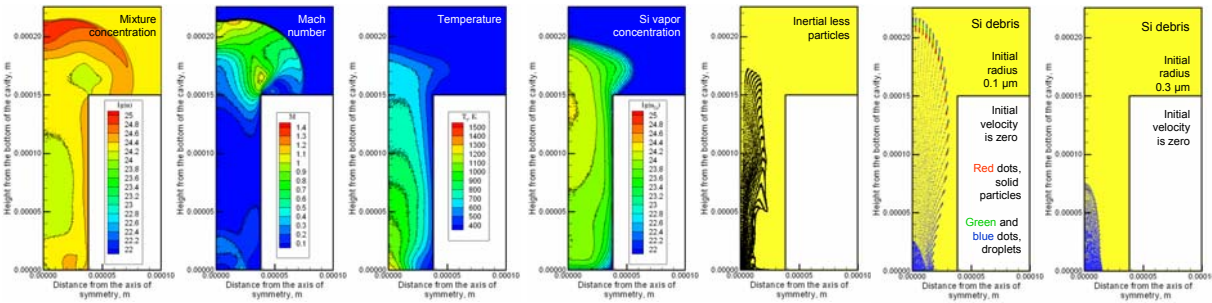


Plume expansion into air at 0.1 bar (time 151 ns), cavity aspect ratio is equal to 2



- Initial stage of the plume expansion inside the cavity is characterized by very complex flow structure due to reflection of shock waves from the cavity wall and their unsteady interference.
- When the shock wave has left the cavity, the gas macroscopic velocity in the cavity becomes relatively low. Therefore, at this stage of the process the transport of Si vapor to the cavity wall occurs primarily by diffusion.
- In the case of HFC ambient the Si vapor concentration near the cavity wall and the flux of re-deposited atoms are much less than in the case of air ambient. The effect is especially significant at the wall near the bottom of the cavity

Plume expansion into gas at 0.1 bar (time 351 ns), cavity aspect ratio is equal to 2



- Propagation of the shock wave in the cavity through HFC ambient gas is half the comparable speed in air surroundings.
- In HFC surroundings droplets are preferentially solidified. Therefore, it is likely, that in HFC surrounding the debris re-deposited at the target surface are solid particles, while in case of air they are still liquid droplets.
- Large debris (with radius of approx. 1 μm) can leave the cavity only if they gain high initial velocity during their formation at the "bath" of molten silicon.

Conclusion

- Flow structure inside the cavity remains very complex until the shock wave leaves the cavity. Later on, the macroscopic velocity in the cavity becomes quite small.
- Transport of Si vapor to the cavity wall is controlled by diffusion. In HFC surroundings, the Si vapor concentration in the near-wall region can be in several times less than in air surroundings. It suggests significant decrease in the flux of re-deposited atoms in HFC gas as compared with air.
- The shock wave speed in HFC surroundings is half that compared with air. This helps the solidification of debris in HFC surroundings.
- The results obtained help to understand the role of the ambient gas in debris removal during multi-pulse laser micromachining of high-aspect ratio slots in silicon wafers.

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