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Microscopic visualization of laser cleaning mechanisms

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The removal of tiny particles adhered to surfaces poses a challenge to IC fabrication, space optics, high resolution and high power optics, large area displays, magnetic storage devices and other critical surfaces. Various cleaning techniques (wet chemical cleaning, scrubbing, pressurized jets and ultrasonic processes) currently used to clean critical surfaces are limited to the removal of micrometer-sized particles and some of them can even damage the wafer. In order to efficiently remove sub-micrometer or even smaller, sub-100nm particles from critical surfaces of various materials without their damage, non-contact dry and steam laser cleaning techniques (DLC,SLC) were developed in the early 90s. DLC can efficiently remove particles by “trampoline” and “hopping” accelerations occurring during thermal expansion of the substrate or the particles themselves, respectively. Eventually, DLC was recognized to have very limited capabilities for cleaning of sub-100nm particle contaminants because of higher particle accelerations required for removal and available only at higher laser fluences at the expense of laser damage of the substrate, and stronger re-deposition of smaller particles back on the substrate. To extend its capabilities to removal of sub-100nm particles, different DLC modifications like laser-induced plasma (LIP) cleaning were proposed to increase particle acceleration without related substrate damage, and auxiliary tools based on thermophoresis or suction were employed to reduce particle re-deposition. In contrast, SLC has none of the abovementioned crucial DLC limitations, exhibiting quite low, particle *size-independent* (“universal”) cleaning threshold fluences and little or no indications of particle re-deposition. In this cleaning mechanism, chemically pure condensed vapor acts as an energy transfer medium (ETM) between the laser radiation and the critical substrate and/or particles. The ETM vapor, upon condensation, forms either droplets or a uniform thin layer on the substrate depending on the ETM-substrate interaction. The substrate is irradiated by the laser at a specified time after the ETM dosing pulse, causing the critical surface to undergo a rapid temperature increase to $0.9T_{cr}$ (where T_{cr} is the critical temperature of the low-boiling ETM). Then, the nanometer-thick superheated, pressurized ETM sublayer in the vicinity of the substrate undergoes explosive boiling, pushing the entire ETM layer to lift off from the substrate. The transient pressure of the superheated ETM may be applied underneath the contaminant particles as a “vapor piston” force, while the lifting-off ETM also exerts a viscous “drag” force on the particles. Importantly, lifting off distances for sub-micrometer ETM layers may approach sub-millimeter magnitudes, enabling the removal of contaminant particles from the surface sufficiently far away to prevent their re-deposition irrespective of their sizes. Also, laser cleaning mechanisms switch between DLC, SLC or combined ones depending on wetting of particle contaminants by particular ETMs, and changing cleaning efficiencies by reducing particle-substrate adhesion strength in the presence of specific ETMs. In this work we studied SLC of organic and inorganic contaminating particles pre-deposited on commercial Si wafers and dosed with variable amounts of de-ionized water or 2-propanol ETMs. Before cleaning, microscopic visualization of particle-ETM-substrate interaction has been performed revealing important peculiarities of particle-ETM and ETM-substrate coupling for different particle/ETM combinations. The subsequent laser cleaning has demonstrated strong impact of ETM state on substrate surfaces and around contaminating particles. Experimental dependencies of laser cleaning thresholds represented vs. ETM dosing times support basic cleaning mechanisms (DLC, SLC or combined ones) proposed on the basis of

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the preliminary visualization experiments. These results demonstrate high practical importance not only of the particle-substrate, but also ETM-substrate and particle-ETM interactions.