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Internal laser writing inside semiconductors by ultrafast pulses

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Intense infrared lasers can be focused inside semiconductor materials to induce localized modifications arbitrarily in the three-dimensional space. This holds strong potential to integrate multiple functions on a single micro-electronic chip including photonics (waveguide/grating/lens), microfluidic (cooling channel), and mechanics (MEMS), etc. To meet these strong technological perspectives, there are today continuously increasing efforts to improve the precision and stability of 3D laser writing of semiconductor (LWS). Different laser pulse durations ranging from few tens of femtoseconds to nanoseconds have been investigated in this context. Among them, the shortest pulses are of strong interest because they must allow achieving high precision and refractive index writing that are not possible without relying on ultrafast material responses. This is also supported by similar developments made in dielectrics during the last decades. However, previous research shows that ultrashort laser pulses suffer from much stronger nonlinear effects inside semiconductors than in dielectrics. These severely deteriorate the applied laser focusing conditions and cause strong difficulties to exceed permanent modification thresholds.

In this talk, first we give an overview on recent literature regarding ultrafast LWS using pulse duration smaller than 1 ps. A comparison among the literature shows that some inconsistencies persist on the appropriate conditions for LWS [1]. To solve this contradiction, we reveal how the temporal contrast of the pulses should not be ignored as it leads to a laser-technology-dependent conditions for LWS. This is supported by modification experiments showing that femtosecond pulses with contrast as low as 10^{-6} can lead modifications inaccessible with high-contrast femtosecond pulses. To reveal the underlying mechanisms associated with ultrafast LWS, we measure the microplasma induced inside Si and GaAs by ultrafast shadowgraphy and luminescence imaging [2]. The latter reveals in particular a large-scale low-density plasma formed the prefocal region that strongly affecting the energy delivery to the focus.

After confirming the difficulties of ultrafast LWS, we propose solutions to cross the threshold conditions for LWS with high-contrast ultrafast lasers. Our first proposed solution relied on hyper-focused femtosecond pulses (sub-100-fs) to achieve permanent modifications inside silicon [3]. For more practical solutions, we propose new alternatives based on temporal shaping of the ultrafast pulses. First, we investigate the writing conditions with stretched pulses up to the picosecond regime [4]. This allows us to report on the minimal pulse duration for LWS with conventional machining configurations. Another approach is to rely on transient accumulation strategies. To this aim, we generate and apply ultrafast trains of pulses at repetition-rates up to THz [5]. Taken these approaches together, we introduce unique multi-timescale control parameters exploited for improved energy deposition and for demonstrations of reliable 3D laser writing deep inside silicon chips that would not be possible otherwise.

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