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Direct nanosecond laser welding of semiconductor materials

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Abstract: We provide a first solution to the challenging problem of direct laser micro-welding of semiconductors. Infrared nanosecond pulses applied on an optical contact between similar and dissimilar materials systematically create shear joining strengths >10 MPa. © 2022 The Author(s)

Ultrafast laser welding is an advanced manufacturing method applied nowadays in various domains. It relies on the use of tightly focused femtosecond pulses that allows high energy deposition by nonlinear absorption anywhere in the three-dimensional space inside/through transparent materials. In turn, highly localized material melting is achieved and constitutes the basis of femtosecond laser welding [1]. Among others, several successful demonstrations include through-glass [1,2], through-polymer [3], or through-ceramic welding configurations [4]. While microelectronics would certainly benefit from this method, it is striking to realize that such process cannot be straightforwardly applied to silicon (Si) and other semiconductors.

Current approaches for Si and general semiconductor wafer bonding rely on intermolecular bonds that appear when two wafers are appropriately prepared and placed in the most intimate contact [5]. However, the resulting bond strengths are relatively modest (few kPa) and need to be enhanced by additional processes like thermal annealing, plasma activation, or electric fields, yielding strengths of several MPa, a level of performance appropriate for most applications [6]. A major drawback of this technique in the assembling of functional devices is the need of multiple and tedious steps in clean room facilities. In this context, a more direct technology as laser micro-welding becomes highly desirable for increased flexibility and the fabrication of complex-architecture semiconductor systems inaccessible by current methods.

Recently, the first successful attempt on through-Si welding has been reported by translating the ultrafast regime into the infrared (IR) domain achieving welding of Si on copper (Cu) [7]. A major limitation in such a configuration relies on the strong propagation nonlinearities inherent to narrow gap materials, which tend to defocus and delocalize the intense IR radiations. This renders internal semiconductor processing very hard unless compensation measures are taken by adjusting the spatiotemporal characteristics of irradiation [8]. More precisely, to circumvent these issues, 10-ps pulses for reduced power delivery were applied to achieve Si-Cu welding [7]. However, the obtained bonding strengths (~ 2 MPa) remained relatively modest in comparison to the best bonding strengths routinely achieved in glass-metal welding studies [9]. After performing numerous unsuccessful attempts of Si-Si welding by using pulses at 1550-nm wavelength and pulse durations from 200 fs up to ~ 20 ps (not shown here), we confirm important physical limitations with intense pulses.

To circumvent the impossibility of directly translating the excellent performances of ultrafast laser glass welding to semiconductor welding, we propose in this work a disruption in the approach and the use of the long pulse regimes. This is inspired by the stealth dicing technology, a major successful application of modifications below the surface of semiconductors by nanosecond lasers [10]. The key aspect of that approach is to exploit a local thermal runaway accessible with near-IR nanosecond pulses causing a locally melted volume near focus under the surface that results in weak points for subsequent dicing. This is the exact analog desired situation for welding except that the below-surface modifications are produced at the semiconductors interface with the intention to create bonds between them.

In this work, we study the potential of this heat-driven processing method to address the question of laser welding of Si and other semiconductors. The employed nanosecond laser setup (5 ns pulse width, 1550 nm central wavelength, and 1 kHz repetition rate) leads to a situation that we extricate from the important nonlinear propagation features found in previous attempts with ultrashort pulses [7]. Precise localization of the energy deposition at the semiconductor interfaces, as represented in Fig. 1a, becomes then achievable by simple pre-optimization procedures, which should result in melting, resolidifying, and bonding

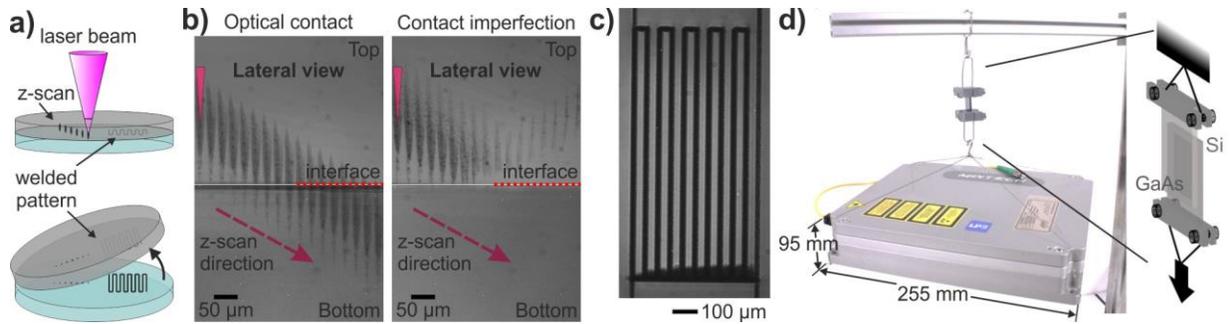


Fig. 1. a) Schematic representation of the welding procedure. b) Lateral view by IR transmission microscopy of the Si-Si interface. Imperfect contact leads to beam reflection at the interface and faulty welding. c) IR transmission image of a welded serpentine in the Si-GaAs configuration. Based on estimations the total welded area of $\sim 0.25 \text{ mm}^2$ should resist shear force up to 4.5 N. d) Image of the laser source used in the experiments ($\sim 3 \text{ kg}$) hanging from a Si wafer welded on GaAs. A schematic representation is shown on the right.

First, by single-spot modifications (1000 pulses at $11 \mu\text{J}$) focused (0.45 NA) at the interface between stacked Si (100) wafers (Fig. 1b) we identify that small imperfections in the contact constitute a Fabry-Perot cavity due to the high refractive index inherent to narrow gap materials. This leads to a high sensitivity of the delivered energy distribution to contact imperfections, which has no equivalent in any other laser welding applications. Relying on regions in optical contact, we later produce lines varying the irradiations conditions (including focus position and scan speed). After optical and confocal inspection of the irradiated surfaces, we determine the optimum irradiation conditions causing the most material mixture between wafers. We then raster-scan the optimized beam (Fig. 1c) producing a large welded area. By shear force measurements, we demonstrate a joining strength of $32 \pm 10 \text{ MPa}$ for the Si-Si configuration. Later, we extend this optimization work to gallium arsenide (GaAs) and test different configurations alongside with Si finding shear joining strengths $> 10 \text{ MPa}$ in all processed cases [11].

To our knowledge, this provides not only the first demonstration of laser welding for similar semiconductors but also dissimilar ones (Si and GaAs). The bonding strengths are similar to those obtained by molecular wafer bonding techniques and ultrafast laser welding of transparent dielectrics, a technique inapplicable for semiconductors with conventional laser processing configuration. In the context of these comparisons, the obtained results lead to an unprecedented process efficiency, given the reported bonding strength and the very compact fiber laser source used to create the bonds. To illustrate this aspect, we realized that a few millimeters weld allows hanging the employed laser equipment ($\sim 3 \text{ kg}$), as it is shown in Fig. 1d after processing a $3.5 \times 7 \text{ mm}^2$ area of the Si-GaAs configuration. We anticipate that the process can be advantageously scaled up to large wafers with the use of industrial high-power sources. This holds great potential for a unique additive manufacturing solution applicable to semiconductors.

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