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Characterization of strain fields around Through-Silicon Vias by second-harmonic scanning microscopy

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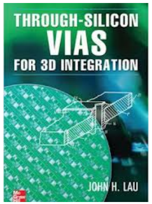
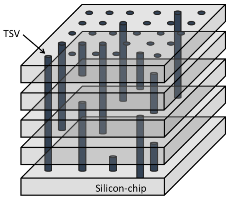
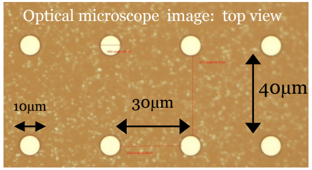
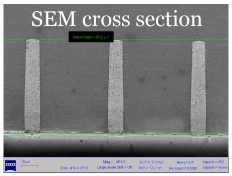
3D integration is a forefront technique for achieving high transistor density while reducing inter-chip RC delay and power consumption. "Through-Silicon Vias" (TSVs) achieve 3D integration by interconnecting vertically stacked devices. These short vertical interconnects enable better electrical performance and consume less power than longer interconnects needed in 2D integration. Cu is widely used as the TSV material because it is compatible with back-end-of-line processes, and has favorable electrical and mechanical properties. However, the large mismatch in coefficients of thermal expansion between Cu and Si induces thermal stresses during fabrication, testing and operation of TSV structures that can induce defects that degrade carrier mobility within the strain field, voids within the metal interconnect, and cracking of the Si wafer. A strong need exists for fast non-invasive methods of characterizing strain fields surrounding TSVs. Here we show that scanning SHG microscopy is sensitive to these strain fields. Even though SHG is forbidden to lowest order from unstrained bulk Si, strain gradients break the centrosymmetry of the diamond-structure lattice, creating a second-order dipolar optical nonlinearity.





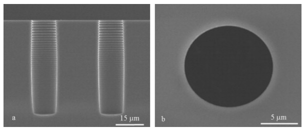
Overview: The semiconductor industry has traditionally followed Moore's Law by down-scaling integrated circuits in 2D. TSVs open up the third dimension.





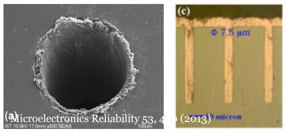
Fabrication of TSVs.

(1) Deep Reactive Ion Etching



- photoresistive mask created on Si surface
- exposed areas etched by SF_6/Ar gas
- sidewalls of initial etched feature protected with fluorocarbon to minimize lateral etching

(2) Laser Drilling + Electrochemical Deposition



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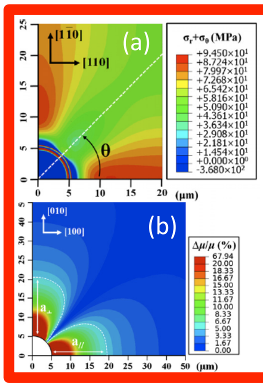
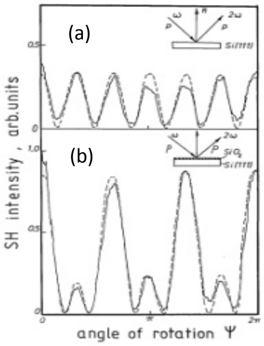
- 266 nm laser creates cleanest sidewall
- single step processing w/o mask
- Debris, rough sidewall are disadvantages
- holes filled by Cu electro-deposition



Induced strain field: mismatched thermal expansion coefficients of TSV and Si strain the surrounding Si. The plots show (**a**) anisotropic contour of sum $\sigma_r + \sigma_\theta$ of in-plane normal stresses, and (**b**) resulting electron mobility degradation at depth z = -0.2 µm beneath Si surface around a TSV of 10 µm diameter and 200 µm height under thermal load ΔT = -270 C, calculated by 3D finite element analysis.

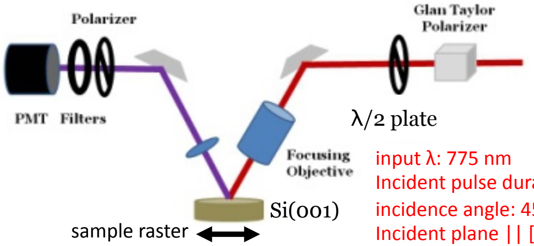
Jiang *et al.*, *Microelectronics Reliability* **53**, 53 (2013)

SHG probe of strain: Unstrained c-Si is inversion-symmetric, so $\chi^{(2)} = 0$ in the dipole approximation. Inhomogeneous deformation of the Si lattice breaks inversion symmetry, creating a strong dipole source of SHG. Govorkov *et al.** observed strain-induced SHG from films deposited on substrates with mismatched thermal expansion coefficients or from heavily-doped samples. Figure shows SHG from (**a**) reference Si(111) sample and (**b**) Si(111)/SiO_2. Oxide-induced strain enhanced SHG by 20x.



*J. Opt. Soc. Am. B **6**, 11117 (1989)

SHG scanning microscope: Strain fields extend only ~10 µm around TSVs. To resolve them the incident laser pulse was focused tightly to $w_o < 2$ µm with a microscope objective. The sample was raster-scanned in 0.1 µm steps while SHG was monitored. All combinations of S/P input and output polarization were used.



input λ: 775 nm
Incident pulse duration: 100 fs
incidence angle: 45°
Incident plane || [100] or [110]

Discussion (cont'd). The observed SHG signal from the strained annulus around each TSV is proportional to:

$$I^{(2\omega)}(\phi) \propto \left| \vec{P}^{(2\omega)}_{surf} + \vec{P}^{(2\omega)}_{BQ} \cos 4\phi + \vec{P}^{(2\omega)}_{strain}(\phi) \right|^2$$

We are developing a quantitative phenomenological theory of the results based on this framework. We welcome your input. Contact: Mike Downer (downer@physics.utexas.edu).

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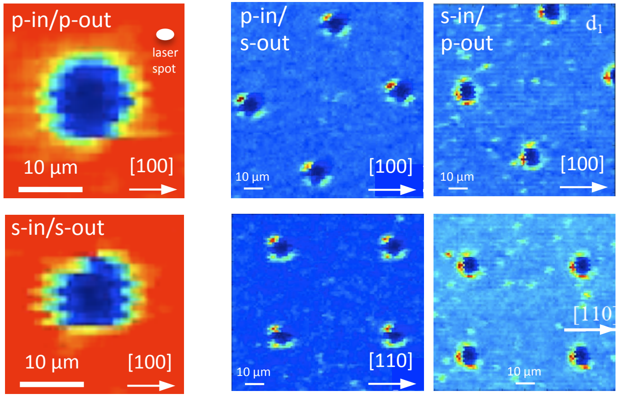
Results. SHG is altered in a ~3 µm wide annulus around the TSVs in all polarization configurations: we observe (**a**) *isotropic* alteration in p-in/p-out and s-in/s-out configurations, and (**b**) *anisotropic* enhancement in p-in/s-out and s-in/p-out configurations. In the latter cases, the anisotropic pattern rotates with the incident plane.

(a) isotropic **(b) anisotropic responses**



Discussion. Far from the TSVs, SHG originates from an isotropic surface polarization $\vec{P}^{(2\omega)}_{surf}$ and anisotropic bulk quadrupole polarization $\vec{P}^{(2\omega)}_{BQ} \cos 4\phi$. Near the TSVs, an anisotropic strain-induced polarization $\vec{P}^{(2\omega)}_{strain}(\phi)$ also contributes.