SEE laser testing using two-photon absorption:

Modeling of charge deposition

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Context & motivations

- Modeling of laser testing
  - Charge deposition profile for TCAD analysis
  - Estimation of equivalent laser LET for adjusting experimental parameters

- Single-photon absorption technique
  - Model of charge deposition: simple or advanced models available
  - Equivalent laser LET
    - Theoretical models available
    - Many empirical results available
    - Strongly dependent on optical parameters (wavelength, pulse duration…)

- Two-photon absorption
  - Model of charge deposition: only basic models available
  - Equivalent laser LET
    - A few empirical results available (Schwank et al, IEEE TNS 2011)
  - Impact of complex nonlinear effects on 3D resolution?

⇒ Development of a realistic model of TPA-induced charge deposition

Outline

- Principles of two-photon absorption (TPA)
- Basic model of TPA-induced charge deposition
- Linear and nonlinear effects
- Advanced modeling of TPA-induced charge
  - Principles
  - Preliminary results
- Conclusions
Single- vs Two-photon absorption

Linear (single photon) absorption

Two-photon absorption

Interband absorption

Free carriers absorption

Non-linear absorption

\[ \alpha \]

\[ \beta \]

\[ \alpha_{IB} \]

\[ \alpha_{FC} \]

Charge generation

SP\\A

TPA

\[ \hbar \omega \geq E_g \]

\[ E_C \]

\[ E_V \]

\[ \hbar \omega \]

\[ \frac{E_g}{2} \]

\[ E_C \]

\[ E_V \]
Two-photon absorption

- **Nonlinear process**
  - Charge generation rate varies quadratically with laser intensity
    \[ G(r, t) \propto \beta \frac{I(r, t)^2}{2\hbar \omega} \]

- **Condition on photon energy**
  - Smaller than band-gap, else linear (single photon) absorption will always dominate
  - Higher than half the band-gap

- **Condition on intensity**
  - Low probability mechanism: \( \beta \approx 1 \text{cm/GW} \)
  - High intensity required for significant charge generation: small spot, short pulse (fs)
TPA pros and cons

- Lateral resolution improved by $\sqrt{2}$

- Axial resolution = access to 3D resolution

- Requires femtosecond pulses
  - Laser source cost

- Quadratically sensitive to uncontrolled intensity variations
  - Energy stability
  - Spot size variations
  - Backside quality of the sample

- More sensitive than SPA to focus variations
  - Not the first choice for scanning large areas
Basic models

- First order approach
  - Consider that absorption is negligible
  - Calculate intensity distribution in the absence of material interaction
  - \( G(r, t) \propto \beta \frac{I(r, t)^2}{2\hbar\omega} \)

- Plane wave approach
  \[
  \frac{dI}{dz} = -\alpha I - \beta_2 I^2
  \]

\[
I(z) = I_0 \frac{e^{-\alpha z}}{1 + \frac{\beta_2 I_0}{\alpha} \left(1 - e^{-\alpha z}\right)}
\]

- Both approaches cannot account for real laser-silicon interaction processes

McMorrow et al, IEEE TNS 49, 6, 2002

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Experimental Characterization of TPA spot in Si

Shao et al, Optics express, 2011
Applications of TPA laser testing

- Same applications as SPA
- 3D « sensitive volume » characterization
  - SET in LM324 op amp
  - SEB in Power MOSFETs
  - SEL in 130nm SRAM

Faraud et al, IEEE TNS 2011
Darracq et al, IEEE TNS 2012
Jaulet et al, NSREC 2008
Optical propagation mechanisms to consider

- Static free carriers absorption
  - Beam attenuation through the bulk
- Depletion
  - Beam attenuation around the focus if significant two-photon absorption
- Kerr effect
  - Refraction index variation with intensity
  - Radial profile of intensity can lead to self focusing, filamentation, destruction…
  - Time profile of intensity can lead to phase modulation
- Plasma effect
  - Carriers generated by the front of the pulse can affect both the refractive index and the absorption coefficient

- These effects may have an impact on:
  - Radial profile: spot size, lateral resolution
  - Axial profile: axial spot extension, axial resolution
  - Time profile (assumed to be negigible)
  - Amount of generated charge
Kerr and Plasma effects on focusing

Refractive index: \[ n = n_{Si} + \Delta n_{Kerr}(I) + \Delta n_{fc}(N) \]

- \( \Delta n_{Kerr} \) = Convex lens
- \( \Delta n_{fc} \) = Concave lens

- Which effect is predominant? Do they compensate each other?
- Is there a threshold energy at which those effects become non negligible?
Modeling options

- Analytic (closed form) model
  - Starting from Maxwell equations
  - No analytic solution in the general case of nonlinear propagation

- Finite Element method
  - Finite Difference in Time Domain (FDTD)
  - Maxwell equations resolved by discretizing space and time
  - To date: available open source and commercial tools do not deal correctly with nonlinear propagation
  - Some results with proprietary two-temperature FDTD model (Bogatyrev et al, J. Appl. Phys., 2011)
  - Time and computation resources required

- Intermediate solution: iterative numerical model
  - Main assumption: the beam remains Gaussian
  - Discretization of space and time
  - Iterative propagation of the Gaussian envelope in space and time using analytic equations and complex ABCD matrices
Iterative numerical model

- **Principles**
  - Time and optical axis (substrate thickness) discretized into slices
  - Each time slice of the Gaussian pulse is propagated through all the substrate slices, calculating charge generation
  - Gaussian radial profile calculated in each substrate slice using complex ABCD transport matrices, taking into account charge generated at previous times

- **Included effects**
  - Static free carrier absorption
  - Depletion
  - Kerr effect on radial profile
  - Plasma effect

- Phase modulation not included in the model
- Material optical properties and laws taken from the literature
- Provides intensity and charge distribution vs space and time
- Implemented in C++ and Matlab
- First sets of results, refinements in progress
Model results: charge track profile

- Wavelength: 1.3µm
- Pulse duration: 100fs
- Substrate doping: $10^{18}$ cm$^{-3}$
Model results: charge track profile

500 pJ
Model results: charge track profile

2nJ
Model results: charge track profile

5nJ
Model results: charge track profile
SPA vs TPA

- SPA 1nJ
  - Wavelength: 1.064µm
  - Pulse duration: 30ps

- TPA 1nJ
  - Wavelength: 1.3µm
  - Pulse duration: 100fs
Equivalent LET

\[ LET_{TPA} = \frac{1}{d} \iint \limits_{LET \ box} N_{TPA}(r) \, dr \]

- Not to be taken as an absolute value, but it provides a practical way of quantifying the influence of experimental parameters on charge deposition.
Propagation mechanisms competition in range of interest

- Kerr effect limits the accessible range of very high LET that are commonly achieved with SPA
Significant contribution of plasma effect in thick substrates reduces the equivalent LET
Effect of LET box thickness

- Effect induced by rapid axial variations of the charge profile in the focus region
- Effect more important for thin substrate because mainly related Kerr effect
- Charge deposition almost homogeneous along 5µm within the LET range of interest
Conclusions

- A new numerical model of charge deposition by TPA laser testing
- Some progress towards a better quantification of charge injection with the TPA technique
- Several propagation mechanisms compete within the energy range of interest for TPA testing
- The model allows quantifying axial spot displacement vs energy
- Model refinements and optimization in progress