Physically Rigorous Modeling of Sensing Techniques Exploiting the Thermo–Optical and Electro–Optical Effect

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ABSTRACT

The complex refractive index in semiconductors depends on several electrical, thermal, and mechanical state variables, e. g. carrier concentrations, lattice temperature, or mechanical stress. Making use of these dependencies, various internal laser probing techniques and optical microsensors have been proposed. In this work, we present a physically rigorous simulation strategy for the complete measurement procedure of laser probes, which is equally applicable to optical microsensors. It includes a self–consistent electro–thermal device simulation, the calculation of the resulting modulation of the refractive index, and the calculation of the beam propagation through the device under test, the lenses and the aperture holes. As an application example, simulation results for laser deflection measurements are discussed.

Keywords: simulation of laser probing techniques, electro–thermal simulation, modeling of beam propagation, thermo–optical effect, electro–optical effect

INTRODUCTION

Recently, various laser probing techniques (e. g. [1], [2], cf. fig. 1) have been introduced, which enable the experimental determination of carrier concentrations and lattice temperature in the interior of semiconductor devices by exploiting the electro–optical and the thermo–optical effect. A related principle has been employed for optical temperature and energy microsensors [3]. For a correct interpretation of the measurement results numerical simulations have shown to be indispensable [4], [5]. Up to now, carrier concentrations and temperature distributions are calculated by electro–thermal device simulation and compared with the experimental values which are extracted from the measurement signals. However, the evaluation of the measurement signals is based on geometrical optics, thus neglecting effects arising from wave propagation and the finite lateral extension of the laser beam. A basic approach for a physically rigorous simulation of the whole measurement process was presented in [6], where beam propagation is calculated by solving the wave equation. In this work, the boundary conditions for the wave equation have been improved and a model which accounts for the imaging by lenses and aperture holes has been added. In addition, we discuss the application of this simulation strategy to microsystems which optically detect physical quantities that affect the refractive index.

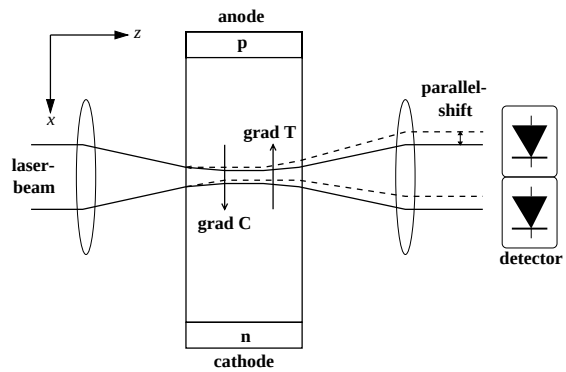

Figure 1: Measurement setup for Internal Laser Deflection measurements. Modulations of the refractive index due to the injection (or removal) of carriers and/or temperature variations cause a deflection of an incident laser beam. A four quadrant photo diode detects both the transmitted intensity (sum of the signals from each segment) and the deflection (difference of the signals from opposite segments).

NUMERICAL SIMULATION ENVIRONMENT

As the electro–thermo–mechanical performance of the device is not affected by the incident laser beam, we follow the simulation sequence sketched in fig. 2. First, the specific operating conditions of the device under test are simulated yielding the state variables which affect the refractive index as a function of space and time. Next, the resulting modulations of the complex refractive index n_{Si} are calculated. Finally, the optical field distribution on the detector is calculated at various points of time by simulating the propagation of the laser beam through the device, the lenses, and the aperture holes. Thus, the time–dependent measurement signal can be calculated in a physically rigorous manner.

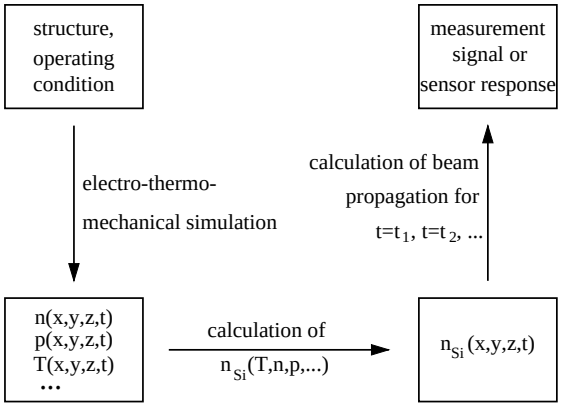

Figure 2: Simulation strategy

CALCULATION OF THE COMPLEX REFRACTIVE INDEX

In the first step, a self–consistent electrical, thermal, and/or mechanical model is employed for calculating the quantities of interest which affect the refractive index. This can be done using a commercially available device simulation tool. In the present work, the distributions of carrier concentration and temperature were obtained from the self–consistent electro–thermal model implemented in the general purpose device simulator DESSIS^{ISE} [7], which solves the coupled system of Poisson's equation, the particle balances for electrons and holes, and the heat flow equation.

As the modulations of the refractive index are small, we may use a first order Taylor expansion to evaluate the resulting effect on the laser beam:

$$n_{Si}(T,n,p,\ldots) = n_{Si,0} + \frac{\partial n_{Si}}{\partial T}\Delta T + \frac{\partial n_{Si}}{\partial n}\Delta n + \ldots$$

Thus, it is sufficient to know the expansion coefficients ([8]–[11]) and we do not have to employ complicated microscopic theories. Note that in general the expansion coefficients depend on the state variables so that they have to be measured at a representative set of operating points if widely differing operating conditions are investigated.

OPTICAL MODEL

Simulation of the beam propagation from the laser to the detector is done by two modules: The propagation through the device under test, i.e. propagation in a medium with inhomogeneous (and in general arbitrary) index of refraction, is simulated by solving the wave equation. On the other hand, the imaging by the lenses and aperture holes is calculated by Fourier optics.

Wave Equation and Boundary Conditions

In the active area of the device, the 2D wave equation with an inhomogeneous dielectric function

$$\left(\frac{\partial^2}{\partial z^2} + \frac{\partial^2}{\partial x^2} + \frac{\omega^2}{c^2} n_{Si}^2(x,z)\right) E_y(x,z) = 0$$

is discretized using finite differences. At the left hand boundary ($z = 0$) the incident wave E_i has to be specified by using the Sommerfeld irradiation boundary condition

$$\frac{1}{2}\left(\frac{1}{ik_z}\frac{\partial}{\partial z} \pm 1\right) E_y(x, z=0) = E_i(x)$$

where $k_z = \sqrt{n_0^2 k_0^2 - k_x^2} = n_0 k_0 \left(1 - \frac{k_x^2}{2n_0^2 k_0^2} + O(k_x^4)\right)$. If the incident wave from the right hand side vanishes, a similar boundary condition holds at the right hand side ($z = z_{max}$). Since k_x writes as the operator $-i\frac{\partial}{\partial x}$ in real space, the Taylor expansion of k_z with respect to k_x^2 yields

$$\frac{\partial E_y}{\partial z} \pm i n_0 k_0 \left(1 + \frac{1}{2n_0^2 k_0^2}\frac{\partial^2}{\partial x^2}\right) E_y$$

$$= 2i n_0 k_0 \left(1 + \frac{1}{2n_0^2 k_0^2}\frac{\partial^2}{\partial x^2}\right) E_i$$

This equation can be easily discretized in real space and represents a sufficiently accurate approximation for angles of incidence up to 15°.

Fourier Optics

The reflected or transmitted waves are projected onto the detector by focussing lenses and aperture holes. This is modeled using Fourier Optics ([12]). We consider a sequence of parallel planes perpendicular to the optical axis and calculate the field distribution $E(x, z_n)$ on the following plane from the field distribution $E(x, z_{n-1})$ on the preceeding plane. For example, propagation along a distance $\Delta z = z_n - z_{n-1}$ causes a phase change in k_x–space, i.e.

$$E(k_x, z_n) = \exp\left(i\sqrt{k_0^2 - k_x^2}\Delta z\right) E(k_x, z_{n-1}),$$

while the projection by a lense is decribed by a phase modulation

$$E(x, z_n) = \exp\left(i\frac{k_0}{2f}x^2\right) E(x, z_{n-1})$$

in real space. Similarly, the aperture holes cause an amplitude modulation in real space.

APPLICATION TO THE INTERNAL LASER DEFLECTION MEASUREMENT TECHNIQUE

The described modeling method has been applied to the simulation of Internal Laser Deflection measurements (cf. fig. 1). During a current pulse, the injected carriers decrease the transmitted intensity (cf. fig. 3). Since the temperature dependence of the absorption coefficient is very small, the signal is expected to remain constant during the pulse. However, self–heating of the device changes the optical interaction length $n_{Si}(T)L$ and thereby the Fabry–Perot transmittance. For high power dissipation or long current pulses, the optical interaction length is changed by several wavelengths so that oscillations are observed on the measurement signal. If $n_{Si}(T)L$ is only changed by a small fraction of a wavelength, as it occurs during short current pulses with low power dissipation (cf. fig. 3), a small drift is observed on the signal.

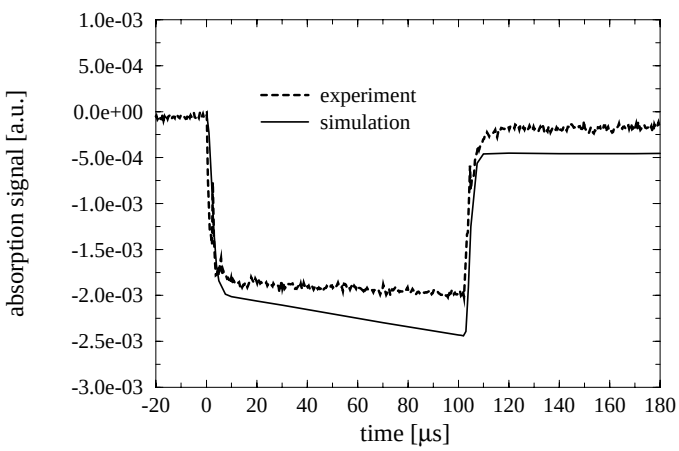

Figure 3: Absorption signal (transmitted intensity) for a power pin diode subjected to a 15 A/cm^2 current pulse of 100 μs duration.

The deflection signal (cf. fig. 4) shows two contributions: Immediately after turn–on, carriers are injected and thereby a carrier concentration gradient is built up which causes a rapid increase of the deflection signal. Similarly, the rapid decrease immediately after turn–off is due to the removal of the carriers. Self–heating of the devices gives rise to a second contribution with a longer time constant. Separating the two contributions, the local carrier concentration and temperature gradient can be extracted from the measurement signal.

As it can be seen from fig. 5, Fabry-Perot oscillations are observed on the deflection signal if power dissipation is sufficiently high to increase the optical interaction length by several wavelengths. The temperature rise ΔT between two interference maxima can be calculated by

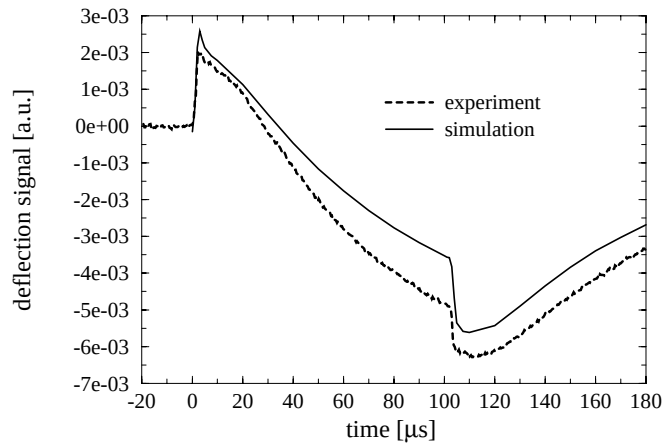

Figure 4: Deflection signal for a power pin diode subjected to a 15 A/cm^2 current pulse of 100 μs duration.

$$\Delta T = \frac{\lambda_0}{2L\frac{\partial n_{Si}}{\partial T}}$$

Unfortunately, for geometrical interactions lengths of some millimeters this temperature rise is in the order of some Kelvin, which easily occurs under typical operating conditions of power devices. For that reason, special preparation techniques, e. g. the deposition of antireflective coatings, have to be employed to reduce this parasitic effect.

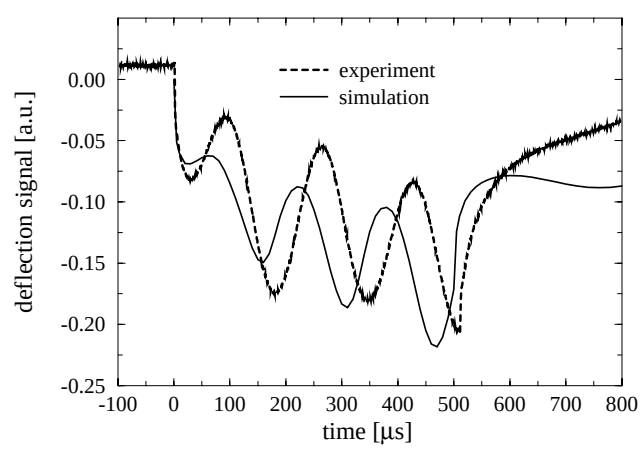

Figure 5: Deflection signal for a power pin diode subjected to a 150 A/cm^2 current pulse of 500 μs duration.

CONCLUSION

We have presented a complete simulation strategy for the physically rigorous modeling of measurement processes exploiting the electro–optical and thermo–optical effects. It constitutes a valuable method for supporting the interpretation and evaluation of the measurement

signals as well as for studying parasitic effects. Similar approaches can be pursued for other optical probing techniques monitoring the absorption, the deflection, or the phase shift of an incident laser beam. It can also be applied to microsensors which detect a physical quantity through the modulation of the refractive index.

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