Helsinki University of Technology

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Instruction Manual for

Modelling of Trap Detectors

Version: 2.2

Date of Issue: December 21, 2005

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1. Introduction

This instruction manual describes the use of models for reflectance and internal quantum efficiency of trap detectors. The models are valid in the range of spectrum between 260 nm and 950 nm. The trap detector in this document is a reflection trap detector containing three silicon photodiodes described more precisely in [1] . Please notice that the main attention in this instruction manual is on the practical use of the models. Instead of describing carefully all theoretical or technical aspects, original sources are referred.

The models added to this manual have been realised by using Microsoft Excel 97. Please notice that principles described in this manual are valid also for every other practical realisation of the same theoretical model. Specific instructions for using the spreadsheet file **TrapModel.xls** are given in Appendix A.

2. Definitions

In this document, the following definitions apply:

UV – wavelength range lower than 400 nm;

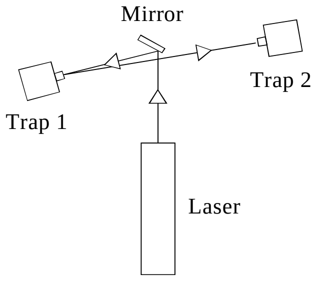
VIS – wavelength range higher than 400 nm.

3. Reflectance model

The theoretical background and the mathematical formulation of the reflectance model are described in [1]. Following steps have to be made to model the reflectance of the trap detector:

- measurement of reflectances of the trap detector;
- fitting the curve of the reflectance model through the measured values;
- evaluation of the results and uncertainty.

3.1 Measurement of reflectances



The measurement setup is described in Fig.1. The laser power is measured by the Trap 1 and the power of the reflected beam by Trap 2. Ratio of these measured

[1] P. Kärhä, *Trap Detectors and Their Applications in the Realisation of Spectral Responsivity, Luminous Intensity and Spectral Irradiance Scales, Thesis for the degree of Doctor of Technology*, HUT, Espoo, 1997, 92 p.

powers is equal to the reflectance of Trap 1, if equality of the reflectances of the traps is assumed.

Distances between traps, mirror and laser should be chosen optimal to minimise the tilt angle of Trap 1 and to avoid divergence of the reflected beam out of the view of Trap 2. Spatial filter can be used to improve the beam quality, if needed.

The reflectances of trap detectors are measured at least at three laser wavelengths. If the laser ligth is linearly polarised, measurements with both s- and p-polarisation should be conducted. The average of these measurements will be used for reflectance modelling. Measurements at lower wavelengths are preferred because of higher reflectance in UV. Wavelengths that are used for the trap responsivity measurements in the cryogenic radiometer should be included. Suggested wavelengths are given in Table 1.

Table 1. Suggested wavelengths for trap detector reflectance measurements

Type of laser	Nominal wavelength, nm	Order of magnitude of trap detector reflectance, %
Argon-Ion	458	0.50
	476	0.45
	488	0.40
	514	0.35
HeNe	633	0.25

3.2 Fitting the reflectance model

The measured reflectance values are used as input data for the reflectance model calculation software. The absolute difference between the measured and modelled reflectance values is calculated for each measured wavelength. The reflectance model has one degree of freedom - the average thickness ***t*** of the silicon dioxide layer on the photodiodes. The fitting of the model curve is realised by changing the parameter ***t*** to minimise the sum of squares of calculated differences. For the Hamamatsu type photodiodes considered here the published values of thickness typically vary between 24 and 30 nm. The refractive indices of silicon and silicon dioxide, needed for the model, are taken from [2], [3] and [4], and also added to this manual in TrapModel.xls file.

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[2] G. E. Jellison Jr., "Optical functions of silicon determined by two-channel polarization modulation ellipsometry," *Opt. Mater*. **1**, 41-47 (1992).

3.3 Evaluation of the results and uncertainty

The uncertainty of the model has been analysed in [5]. Components that should be included in the uncertainty budget of the measurements are listed in Table 2. The agreement between measured and modelled reflectances has to be within expanded uncertainty limits of the reflectance measurements. The uncertainties of the modelled reflectance values $u_{mod}(\lambda)$ should be estimated each time by trial of maximising the model curve fluctuations within fixed uncertainty limits at measured wavelengths.

Table 2. Uncertainty components of the reflectance measurements

Uncertainty component	Comment	Example, %
Repeatability of measurements	Type A, standard deviation of measurements	0.20
Calibration of measured trap detector	Type B, from calibration certificate	0.04
Calibration of reference trap detector	Type B, from calibration certificate	0.04
Spatial nonuniformity of traps	Type B	0.01
Linearity of the trap detectors	Type B	0.01
Current measurement	Type B	0.01
Tilt of the measured trap detector	Type B, depends on the setup	0.05

Uncertainty of the reflectance modelling will be included in the uncertainty budget of modelled responsivities of trap detector. The relative standard uncertainty of the responsivity due to the reflectance measurements and modelling u_r is calculated as

$$u_r(\lambda) = \rho(\lambda) u_{\text{mod}}(\lambda)$$

where $\rho(\lambda)$ is the modelled reflectance of the trap detector at the wavelength λ.

[3] I. H. Malitson, “Interspecimen comparison of refractive index of fused silica,” *J. Opt. Soc. Am*. **55**, 1205-1209 (1965).

[4] E.D. Palik, *Handbook of optical constants of solids*, Academic Press, New York, pp. 547-569 1985.

[5] A. Haapalinna, P. Kärhä, E.Ikonen, “Spectral reflectance of silicon photodiodes,” *Appl. Opt*. **37**. 729-732 (1998).

If the trap detector is used at the same laser wavelengths where reflectances are measured, the modelled values should be used in the responsivity calculations instead of measured values.

4. Internal quantum efficiency model

Theoretical background and mathematical formulation of the internal quantum efficiency (IQE) model is described in [6]. Modelling in visible region is based on work reported by L. Werner [7]. A good reference for UV modelling is [8]. Following steps have to be made to model the IQE of the trap detector:

- reflectance of trap detector has to be measured and modelled;
- responsivity of the trap has to be measured against cryogenic radiometer;
- responsivity of the trap has to be measured against pyroelectric radiometer in UV, if the responsivity will be modelled also in UV;
- fitting the model curve through the measured values;
- evaluation of the results and uncertainty.

4.1 Input data

Measurement and modelling of the reflectance are described in Chapter 3 of this document. Measurement of the trap detector responsivity against cryogenic radiometer is described in Instruction Manual of Cryogenic Radiometer Measurements. For modelling, responsivity values from the calibration certificates of trap detectors are used. Relative responsivity values in UV can be accepted if absolute measurement results are not available. For modelling in UV, values for density of

[6] T. Kübarsepp *Optical Radiometry Using Silicon Photodetectors, Thesis for the degree of Doctor of Technology*, HUT, Espoo, 1999.

[7] L. Werner, J. Fischer, U. Johannsen, and J. Hartmann, “Accurate determination of the spectral responsivity of silicon trap detectors between 238 nm and 1015 nm using a laser-based cryogenic radiometer,” Metrologia **37**, 279-284 (2000).

[8] T. Kübarsepp, P. Kärhä, and E. Ikonen, “Interpolation of the spectral responsivity of silicon photodetectors in the near ultraviolet,” *Appl. Opt.* **39**, 9-15 (2000).

states (DOS) of silicon are taken form [7] and added to this manual in TrapModel.xls file.

4.2 *Fitting the IQE model*

Because of practical reasons, actual fitting of the IQE model is done by fitting the calculated responsivity curve through the measured responsivity values. Responsivity curve is calculated from IQE and reflectance models. There are seven parameters that can be changed in the used IQE model. Parameters are listed in Table 3. Two of them, B and ΔE, describe increase of quantum yield of silicon in UV and have influence only at wavelengths lower than 375 nm.

The fitting of the responsivity curve through the measured responsivity values is done by changing IQE model parameters to minimise the sum of squares of absolute differences between measured and modelled responsivities.

Table 3. Description of IQE model parameters

Symbol	Description	Example value	Unit
$\boldsymbol{P_f}$	Collection efficiency at SiO_2/Si interface	0.962	-
$\boldsymbol{T}$	Depth in the photodiode at which $\boldsymbol{P_f}$=1	0.26×10^{-6}	m
$\boldsymbol{P_r}$	Collection efficiency in the rear region of photodiode	0.997	-
$\boldsymbol{D}$	Depth at which $\boldsymbol{P_f}$ has linearly decreased to the value of $\boldsymbol{P_r}$	13×10^{-6}	m
$\boldsymbol{d}$	Thickness of the photodiode	320×10^{-6}	m
$\boldsymbol{B}$	Scaling factor, includes direct transition-matrix element and doping-condition variations	1.75×10^{6}	m^{-1}
$\boldsymbol{\Delta E}$	Correction for the absorbed photon energy	0.11	eV

It seems that the final fit of the model may depend on the order of steps that are used. Following steps are suggested for the fitting:

[9] M. V. Fischetti and S. E. Wang, “Monte Carlo analysis of electron transport in small semiconductor devices including band-structure and space-charge effects,” *Phys. Rev. B* **38**, 9721-9745 (1988).

1. fit the responsivity curve in VIS by optimising these five parameter values that have influence in that spectral region (P_f, P_r, T, D and d);

2. fit the responsivity curve in UV by optimising parameters B and ΔE; other parameters are kept fixed;

3. fit all curve by changing all parameters; differences between measured points and the model are limited to be smaller than uncertainty limits of responsivity measurements.

4.3 Evaluation of the results and uncertainty

The uncertainty of the IQE model is estimated in [6]. The uncertainty components that should be included in the uncertainty budget are given in Table 4. The agreement between measured and modelled responsivities has to be within expanded uncertainty limits. Results of the modelling should be compared with earlier results. If big differences are observed, the reason for the difference has to be explained.

Table 4. Uncertainty components of modelled responsivities

Uncertainty component	Comment	Example, %
Calibration of trap detector against cryogenic radiometer	Type B, from calibration certificate	0.04
Reflectance modelling	Type B, from reflectance measurements	0.04
Calibration of trap detector against pyroelectric radiometer	Type B, included only for UV wavelengths	0.35
Uncertainty of the IQE model	Type B, depends on wavelength	0.01 - 0.1

5. Reporting Results

Report of the modelling results has to be issued at least in computer file format as internal calibration certificate. Following data has to be included in the report:

- input data
    - measured reflectances;
    - reflectance setup parameters (tilt angle, distances, beam size);
    - responsivities from calibration certificates;
- modelled reflectance values;
- modelled internal quantum efficiency and responsivity values;

- optimised parameters for model functions;
- uncertainty budgets for
  - reflectance measurement;
  - modelled responsivity;
- comparison with previously modelled values, if available.

Modelled reflectance and responsivity values should be preferably reported with 1 nm wavelength intervals.

6. Records

The model files for traps are stored in the following folder:

\\Mart\Documents and Settings\Noorma\My Documents\Traps\Responsivity

7. Intercomparisons and model verifications

The mathematics used for extrapolating reflectances have been compared with calculations done by Justervesenet, Norway (JV) and CSIC, Spain. Reflectances were calculated for a photodiode with 28 nm oxide-thickness for wavelengths 350, 450, 550 and 650 nm wavelengths. HUT and JV used Excel, CSIC used Visual Basic to do the calculations. All three institutes agree well within uncertainties. [Results and correspondence attached in the paper version of this manual].

Reflectance modelling has been verified with a comparison to measured reflectances [Footnote 5]. Spectral responsivity in UV region has been indirectly compared with NPL in [10].

Appendix A: User Guide for TrapModel.xls

The MS Excel file TrapModel.xls can be used as a tool for modelling the reflectance and the IQE of reflectance trap detectors. The file consists of 3 worksheets:

- Reflectance Model that includes the reflectance model
- IQE Model that includes the internal quantum efficiency model

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[10] P. Kärhä, N. J. Harrison, S. Nevas, W. S. Hartree and I. Abu-Kassem, "Intercomparison of characterisation techniques of filter radiometers in the ultraviolet region," *Metrologia* **40**, S50-S54 (2003).

- DOS data that includes densities of states of silicon data from [7]

There are comment fields on both model worksheets that include information about the location of parameter fields, input data fields and model output values. The model worksheets are filled with example data. The imput data has to be changed first to use the models.

The Solver Tool is used to optimise the parameters of the model for the best fit. If solver is opened, it already has ready-to-use locations inserted. In case of IQE modelling in UV, the target field and parameter fields have to be changed.

The file with ready-made model should be saved with file name that includes trap detector identification and date of modelling.

The original model file is located in the following folder:

\\Megamuisti\public\data\MRI_docs\quality\radiom\Instruction Manual for Trap Modelling