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Measurement of free carrier absorption of low doping crystalline silicon at 1550 nm

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Abstract

We report the measurement at room temperature of the free carrier absorption for n and p doped silicon at 1550 nm. Compared to previous study, our measurement are based on the photodeflection technique which allows the testing of low doped samples (impurities concentration ranging from 10^{13} to $10^{17}/\text{cm}^{-3}$). Even if the measured optical absorption is up to three order of magnitude lower than previously done, the derived free carrier absorption coefficient is in good agreement with previous empirical models. In the near infrared transparency region of silicon, the free carrier absorption has also been measured as a function of the wavelength for moderately doped samples.

1 Introduction

While the second generation of gravitational wave interferometer is being installed and commissioned across the world [6], the subsequent generation is being designed. In this framework, the European project named the Einstein Telescope (ET) will consist of two separate underground interferometers sharing the same tunnel. To cover a broad range of gravitational wave sources, the two interferometers will have different working temperatures: one will be cooled down at 20 K (ET-LF) while the other will operate at room temperature (ET-HF) [8].

The room temperature interferometer will rely on the extension of known technologies, already experienced with the second generation interferometers. That is in contrast with the intensive research required to guide the technical choice regarding the cryogenic interferometer ET-LF. In particular the choice of material for the mirror substrate is constraint by some severe requirements to guarantee outstanding mechanical and optical qualities. One of the most promising candidate for the mirrors is currently crystalline silicon and intensive researches are currently underway to characterise its properties [7, 11].

This paper summarizes the measurement done at room temperature on the optical absorption of n and p lightly doped silicon at 1550 nm, the working wavelength of the ET-LF laser. An empirical model is given for the Free Carrier Absorption (FCA) coefficient linking the optical absorption and the free carrier concentration. Our model is compared to previous estimation and the dependency on the wavelength of the absorption in the near infrared is also studied. The absorption as a function of the wavelength in near infrared region is also presented.

Table 1: Average resistivities of our eight samples. The standard deviation is typically less than 5% on such measurement.

	n doped		p doped	
Sample #	Resistivity [Ω.cm]	Dopant concentration [cm^{-3}]	Resistivity [Ω.cm]	Dopant concentration [cm^{-3}]
1	0.17	3.9×10^{16}	0.12	2.1×10^{17}
2	2.8	1.6×10^{15}	2.4	5.7×10^{15}
3	13	3.4×10^{14}	64	2.1×10^{14}
4	808	5.2×10^{12}	621	2.1×10^{13}

2 Presentation of the experiment

This section presents the characteristics of the samples tested as well as our measurement procedures.

2.1 The silicon samples tested

All the samples tested have a similar cylindrical geometry: 50.4 mm in diameter and 20 mm long. The n-type silicon samples are doped with phosphorus whereas the p-type are doped with bore atoms. The two surfaces are plane parallel and polished with a roughness less than 0.5 nm. No optical coating is applied on the samples.

The free carrier concentration is determined from the measurement of the bulk resistivity of each samples. The measurement has been done on five points on each side, and the average is taken for our analysis. The resistivities of our eight samples are summarized in table 1.

We are assuming for our calculations that every dopant atom is ionized which is a valid hypothesis since our samples are not heavily doped (the dopant concentration being less than $3 \times 10^{17}\mathrm{cm}^{-3}$) and the measurements are done at room temperature.

2.2 The absorption measurement techniques

Two complimentary methods are used to measure the bulk absorption of the silicon samples: spectroscopic measurement where the absorption is derived from the transmission of the sample, technique preferred for relatively high doped samples with absorption superior to 0.01 /cm and for lightly doped sampled, the photodeflection technique is used. These methods have already been presented previously [2] and are only reminded here.

Using a spectrophotometer, one can measure the transmission of the samples as a function of the wavelength. Thanks to the large thickness of the samples (compared to the wafer thin samples) one can measure relatively low absorption α with this method ($\alpha > 0.01/cm$). The total transmission T_a for normal incidence is related to the bulk absorption α by the following relationship [1]:

$$T_a = (1 - R^2)^2 \frac{exp\,(-\alpha d)}{1 - R^2 exp\,(-2\alpha d)} \qquad (1)$$

with R the Fresnel reflection coefficient (in power) and d the thickness of the sample. As a reference, the value R^2 is determined by the transmission of the samples with the lowest absorption for n and p doped silicon set. As only light doped samples are tested, the refractive index (and hence R) could be considered constant for all our samples.

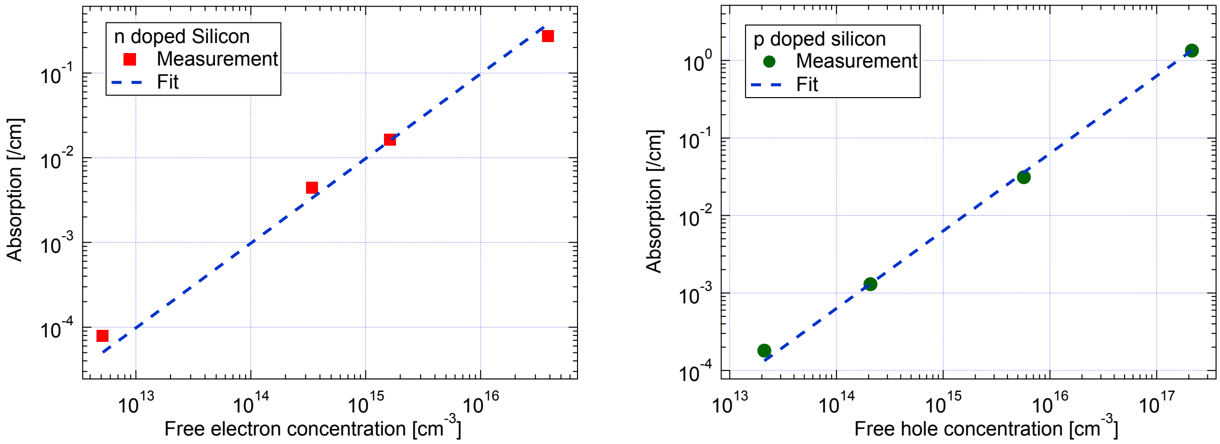

Figure 1: Optical absorption as a function of the free carrier concentration for n (left) and p (right) doped silicon. The fit used to derive the free carrier absorption coefficient is represented by the dash lines.

The second method used to measure the volume optical absorption is the photodeflection technique [5]. This method is not a direct measurement but is extremely sensitive to measure low optical absorption up the order of the ppm/cm. For this technique, two lasers are required: one high power laser (the pump laser) and a second low power laser at a different wavelength (the probe laser). The pump laser is focused on the sample and the small amount of optical power absorbed in the volume is converted to heat and creates a gradient of temperature within the sample under test. The gradient of temperature induces a gradient of refractive which deflects the probe beam when it crosses the pump laser. The deviation of probe beam, proportional to the absorption, is then recorded using a quadrant detector.

3 Results

The measurement of the optical absorption as a function of the free carrier concentration is presented in figure 1 at 1550 nm. As expected the optical absorption is directly proportional to the concentration of the free carrier. Using this data, one can derive a simple expression for the Free Carrier Absorption (FCA) coefficient α_{FCA} for n and p samples which links the optical absorption (in unit of cm^{-1}) to the free carrier concentration (in unit of cm^{-3}):

$$\begin{aligned} \alpha_{FCA,n} &= 9.8 \times 10^{-18} \pm 0.5 \\ \alpha_{FCA,p} &= 6.3 \times 10^{-18} \pm 0.3 \end{aligned} \tag{2}$$

The coefficient (in unit of cm^{-2})given in equations 2 are for a wavelength of 1550 nm. Our data can be compared to previous values found experimentally on samples with much higher doping (with concentation ranging from 10^{17} to 10^{20} cm^{-3}) using photospectroscopic measurement. A comparison of our measurement with the different empirical models is summarized in the table 2.

In the table 2, we have also added the predicted FCA coefficients from the classical Drude model (reminded in section 5). For this model, we have used the mobility at low doping with $mu_e = 1500cm^2V^{-1}s^{-1}$ and $mu_h = 450cm^2V^{-1}s^{-1}$ for electron and hole respectively. As noted by Horwitz and Swanson [4] a correction factor must be applied to the original Drude equation, based on measurement, they found the factor to be 6.3 (so increasing the FCA coefficient). This factor has not been included in the table 2.

Table 2: Comparison of FCA empirical models and the Drude theoretical model.

Model		$\alpha_{FCA,n} \times 10^{18}$	$\alpha_{FCA,p} \times 10^{18}$
Our measurement		**9.8**	**6.3**
Soref & Bennet	[10]	8.5	6.0
Green	[3]	9.7	6.5
Vardanyan	[13]	16.6	8.4
Rüdiger	[9]	5.6	7.4
Drude (theory)	[10]	0.33	0.59

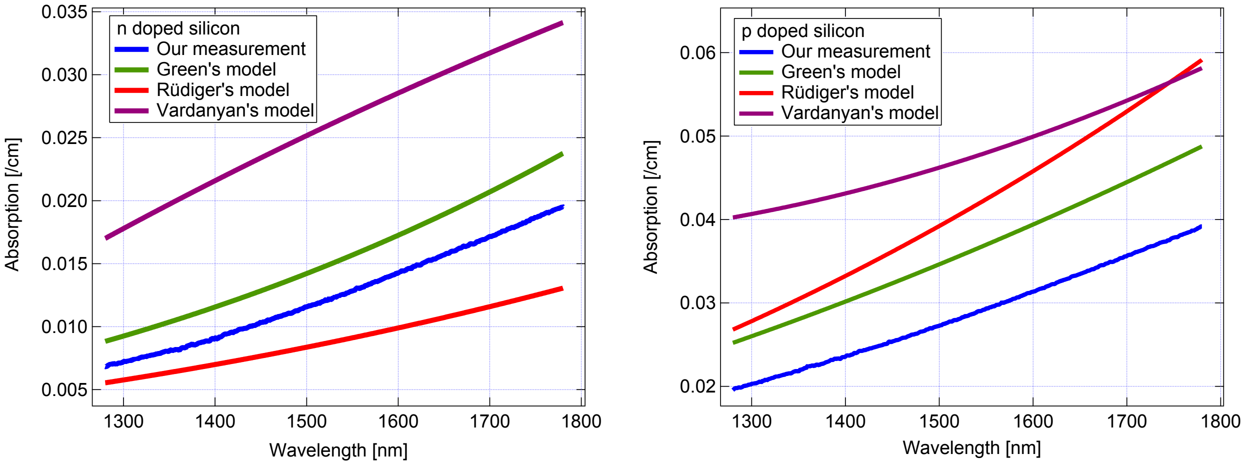

Figure 2: Absorption in the near infrared for n (left, resistivity of 2.8 Ω.cm) and p (right, resistivity of 2.4 Ω.cm) doped silicon. The blue curve is our measurement whereas the three other curves are derived from different empirical models

All the empirical FCA coefficients (derived from the fitting of measurements) presented in table 2 are in reasonably good agreement, with all the coefficients within 60% for the n doped samples and within 20% for the p doped silicon. Our measurement seems to confirm Green's model, since the FCA coefficients found is within 5% of the coefficient predicted by Green. Except for the results of Rüdiger et al., the FCA coefficient for n doped silicon is higher than for p doped samples.

4 The wavelength dependence of the FCA

Regarding the samples number 2 (see table 1), their absorptions are high enough ($\alpha_{FCA} > 0.01$/cm) so we can measure directly their absorption as a function of the wavelength using a spectrophotometer. We focus our measurement on the transparency region of silicon so away from the region where the band gap absorption dominates (i.e. $\lambda > 1280$ nm).

The measurement of the absorption as a function of the wavelength for two silicon samples is shown in figure 2. This plot highlights the various models used to described the FCA in silicon and in particular the difference regarding the dependency of the wavelength with the absorption.

As in the previous section, our values and the profiles of our measurement seems to validate Green's model, indicating that the absorption depends on the cube of the wavelength for the samples doped n and on the square of the wavelength of the p doped samples. For the n doped samples that is a major deviation from the Drude theory where the free carrier absorption is predicted to be proportional to the square of the wavelength.

For p doped sample tested here (the number 2), the measured absorption is lower than what is predicted by other models (lower by 25% from Green's model for example). This particularity was also noticed in figure 1 for a wavelength of 1550 nm, where this sample absorption is slightly lower compared to the fitted curve.

The empirical models of Green and Rüdiger assume the FCA to be only dependent of one power of the wavelength. That is only for the sake of simplicity and not necessary based on physical ground. Using second order perturbation theory of quantum mechanics, the interactions between the photon, electron and phonon can be detailed leading to a new theoretical model for the free carrier absorption [12].

From our measurement, we can deduct that the dominating mechanism for the absorption in n-doped and p-doped samples is different since the dependency on the wavelength is different. Our measurement also shows a FCA coefficient independent of the concentration of impurities that indicates that the measured absorption is not linked to the concentration of ionized impurities.

5 The Drude equation

We remind here the FCA coefficient derived from the classical Drude equation:

$$FCA_{n,p} = \left(\frac{e^3\lambda^2}{4\pi^2 c^3 \epsilon_0 n}\right)\left(\frac{1}{m^{*2}_{n,p}\mu_{n,p}}\right) \tag{3}$$

with e the elementary electric charge, λ the light wavelength, c the celerity of light, ϵ_0 the permittivity of the vacuum, $m^*_{n,p}$ is the conductivity (or thermal velocity) effective mass of electron and hole and $\mu_{n,p}$ the velocity of electron and hole. Replacing the numerical constant from equation 3, numerically, we have:

$$FCA_{n,p}\ [cm^2] = 1.5 \times 10^{-17}\left(\frac{\lambda}{\mu m}\right)^2 \frac{1}{\left(m^*_{n,p}/m_0\right)^2\left(\mu_{n,p}/cm^2V^{-1}s^{-1}\right)} \tag{4}$$

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