Near IR Absorption in Heavily Doped Silicon – An Empirical Approach

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Abstract

Backside failure analysis techniques rely heavily on transmission of near infrared (IR) radiation through the silicon substrate. This statement applies both to emission techniques and active laser probing. Heavy doping of substrates causes them to become highly absorptive in the near IR due to band gap shifts, which effects phonon-assisted absorption, and to free-carrier absorption. Substrate thinning is often required to allow adequate optical transmission. This paper describes an empirical approach to determining the absorption coefficient in a heavily doped substrate and use of the coefficient in determining the amount of substrate thinning required.

Introduction

Absorption coefficients versus wavelength and carrier density are necessary to determine the amount of thinning required for a particular measurement. First principle analysis of absorption in doped silicon has been performed using complex computer models [1]. Use of these models by the "on-the-line" failure analysis engineer is not generally tractable, however. This paper presents results from an empirical approach to modeling optical absorption in heavily doped silicon. The model uses known scaling laws and parameter fitting to experimental data. The derived absorption curves fit the available experimental data within 10%. The empirical model has been placed into a simple spreadsheet, which calculates thinning requirements and displays absorption curves.

Experimental Data

An empirical model utilizes known scaling laws as its foundation. These scaling laws will have a set of unknown coefficients, which must then be fit to experimental data. The measurements of S. E. Aw, et al. [2] form the basis for our model. Their paper appears to be the most recent experimental results of optical absorption in doped silicon. The description of the experimental procedures and the comparison of results to other data [3-5] indicate that this data is fairly reliable.

One area of uncertainty is the reliability of Aw et al.'s method for determining the dopant density. They indicate that these dopant concentrations were determined from the resistivities as measured by the "standard four-point probe technique". Neither an uncertainty, nor potential for an offset bias in this measurement is given by Aw et al.

One typographical error is noted in Aw et al. In their Figure 1, a dopant density of $1.6\text{x}10^{17}$ is listed. However, their Table 1 and Figure 4 both indicate a dopant density of $1.6\text{x}10^{18}$. Analysis of the free carrier absorption portion of their absorption curve (see below) indicates that the second value must be correct. The value listed in Figure 1 is assumed to be a misprint, being off by a factor of 10.

Empirical Model

Phonon-Assisted Absorption

The two main optical absorption effects for doped silicon in the near IR are phonon-assisted absorption and free carrier absorption. As silicon is not a direct band-gap material, direct promotion of an electron from the valence to the conduction band can only occur with the aid of a phonon. Aw et al. present a theoretical framework for the phonon-assisted absorption, which coupled with their experimental results, yields the semi-empirical formula

$$\alpha_{pa}^{1/2} = k_{pa}\left(E_0 - E_{ph} - \Delta E(\rho)\right)$$

for $\left(E_0 - E_{ph} - \Delta E(\rho)\right) > 0$,

else $\alpha = 0$, (1)

where α_{pa} is the phonon-assisted absorption, k_{pa} is a constant, E_{ph} is the photon energy, E_0 is a constant, and $\Delta E(\rho)$ is an energy shift dependent on the dopant density, ρ. The constant, k_{pa} is determined empirically from Figure 3 of Aw et al. to be 58 (1/eV*cm^1/2). E_0 is primarily the bandgap energy, however, other contributions include the longitudinal acoustic phonon energy. It has an empirical value of 1.09 (eV)

The shift in band-gap, $\Delta E(\rho)$, was found by Aw et al. to fit the empirical formula

$$\Delta E(\rho) = k_\rho \, \rho^{1/3} \quad , \qquad (2)$$

where k_ρ has a value of -1.0x10^{-8} (eV*cm) for both n and p doping. No theoretical foundation for this scaling law is given, however, Figure 4 of Aw et al. shows that the fit is very good for their data and in reasonable agreement with other experimental results. Figures 1 and 2 show plots of Eqs. 1 and 2 respectively.

Free Carrier Absorption

In addition to phonon-assisted absorption, photons can be absorbed by the free carriers in the semiconductor substrate. This effect is simply plasma absorption and is characterized by the Drude equation

$$a^{e,h} = k_{fc}^{e,h}\, l^2 N^{e,h} \quad , \qquad (3)$$

where k_{fc} is a constant dependent on the free carrier effective mass and mobility, λ is the optical wavelength, and N is the free carrier density. The superscripts, e and h, stand for electrons and holes respectively. In the case of a substrate with no carrier depletion effects and moderate to high dopant density, the free carrier density is essentially equal to the dopant density. In this case, Eq. 3 can be rewritten as

$$a^{n,p} = k_{fc}^{n,p}\, l^2 r^{n,p} \, . \qquad (4)$$

At wavelengths longer than ~ 1.5 micron, the absorption coefficients plotted in Figures 1 and 2 of Aw et al. are essentially all due to free carrier absorption. The wavelength squared and linear density scaling given in Eq. 4 fits the data very well in this wavelength region. Again, k_{fc} can be empirically extracted from the data and is found to be 3.3x10^{-18} (cm^2/um^2) for p doping and 3.5x10^{-18} (cm^2/um^2) for n doping.

Total Absorption

The total absorption is the sum of the two effects, phonon-assisted absorption and free carrier absorption. The above equations with the empirically derived coefficients were incorporated into an Excel spread sheet with the results shown in Figures 3 -5. A conversion factor of 1.243 (um/eV) is used to convert from photon energy to wavelength.

Figure 3 shows the relative contribution of each of the two absorption effects for a carrier density of 1x10^{19} (1/cm^3). As can be seen, free carrier absorption begins to dominate the absorption at wavelengths longer than 1.030 micron. This crossover point moves to shorter wavelengths as the carrier density is increased.

Figures 4 and 5 show the total absorption coefficient for a range of p and n dopant densities. The agreement between this empirical formalism and the data is generally better than 10% as shown in the example in Figure 6. An exception is for the lower p dopant values and wavelengths around 1.2 micron. A dip occurs in the experimental data at this point that cannot be explained by the two absorption effects. In this limited region, the empirical result will over estimate the absorption coefficient.

In all cases care should be used in applying these results to a depletion region. The free carrier and dopant densities are not necessarily proportional in such a region.

An Example

Many laser based backside-imaging tools utilize YAG lasers, which operate at a wavelength of 1.064 micron. Figures 7 and 8 show the empirically derived absorption coefficient at this wavelength versus n and p dopant levels respectively. To use these coefficients to determine the transmission through substrate, the formula

$$T = (1 - R)^2 \exp(-2ad) \qquad (5)$$

is applied, where R is the surface reflectivity, d is the substrate thickness in centimeters. The factor of two in the exponential accounts for the double pass through the substrate. Use of an anti-reflection coating to reduce R to less than 0.01 is common.

A nominal wafer thickness of 0.1 centimeter with a p dopant level of 1x10^{19} and a negligible surface reflectance is assumed. For this case Eq. 5 combined with absorption coefficient in Figure 8 indicate a transmission of ~ 6x10^{-7}! Clearly some thinning of the substrate would be required in this example. In most optical instruments a certain fraction, f, of the input illumination must be returned. The thinned thickness required in order to achieve this fractional transmission is given by

$$d \le \frac{-\ln\left(f/(1-R)^2\right)}{2a} \; . \qquad (6)$$

Continuing our example, if f needs to be 10%, then the substrate must be thinned to less than 160 microns.

Summary and Conclusions

An empirical model for determining the absorption in doped silicon is presented. The model utilizes simple closed form expressions and four parameters that are derived from experimental data. The model can be readily put into an spreadsheet and utilized to determine thinning requirements for backside analysis of heavily doped substrates.

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References

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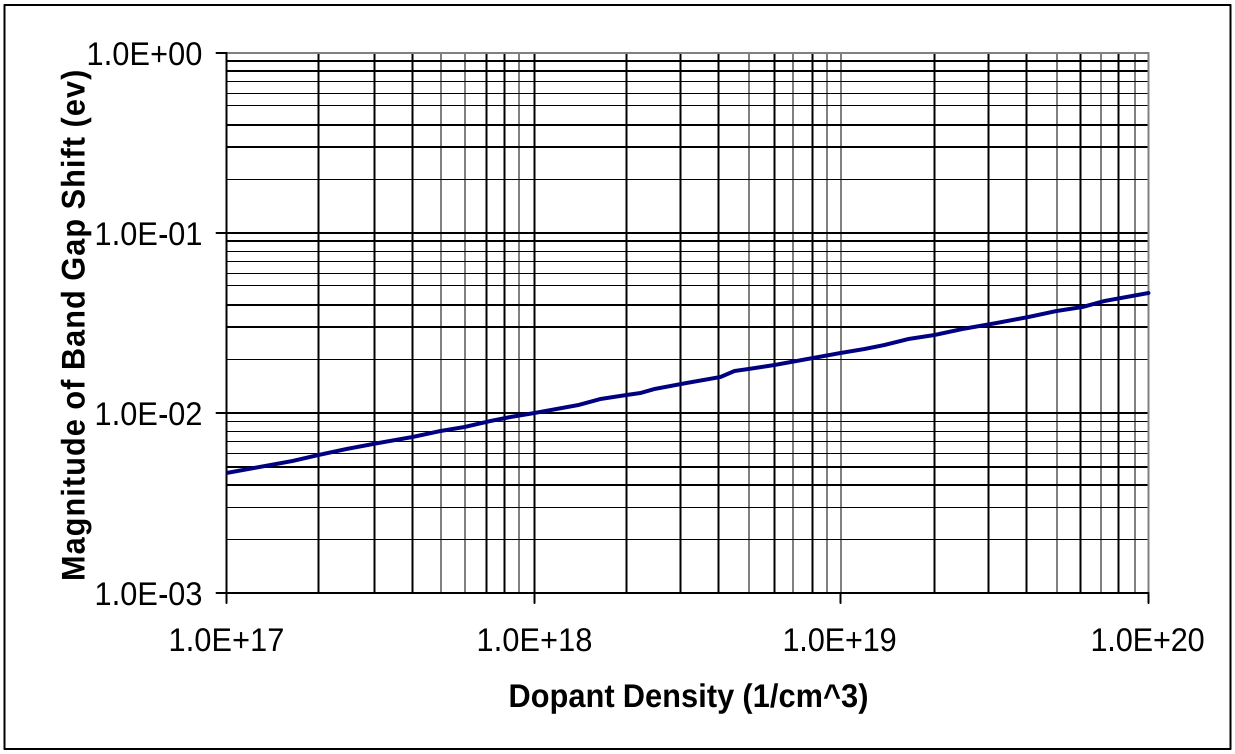

Figure 1 Graph of magnitude of band-gap shift versus n or p dopant density.

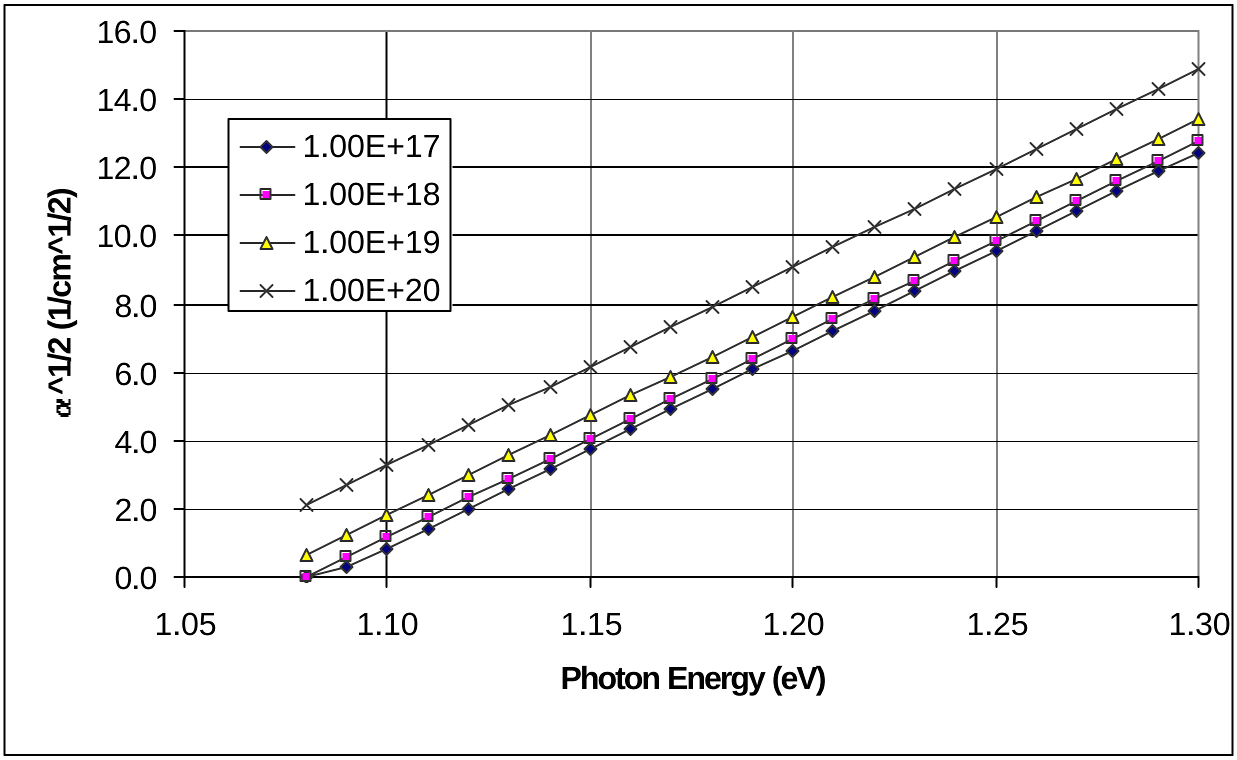

Figure 2 Graph of square root of absorption coefficient versus photon energy for phonon-assisted absorption.

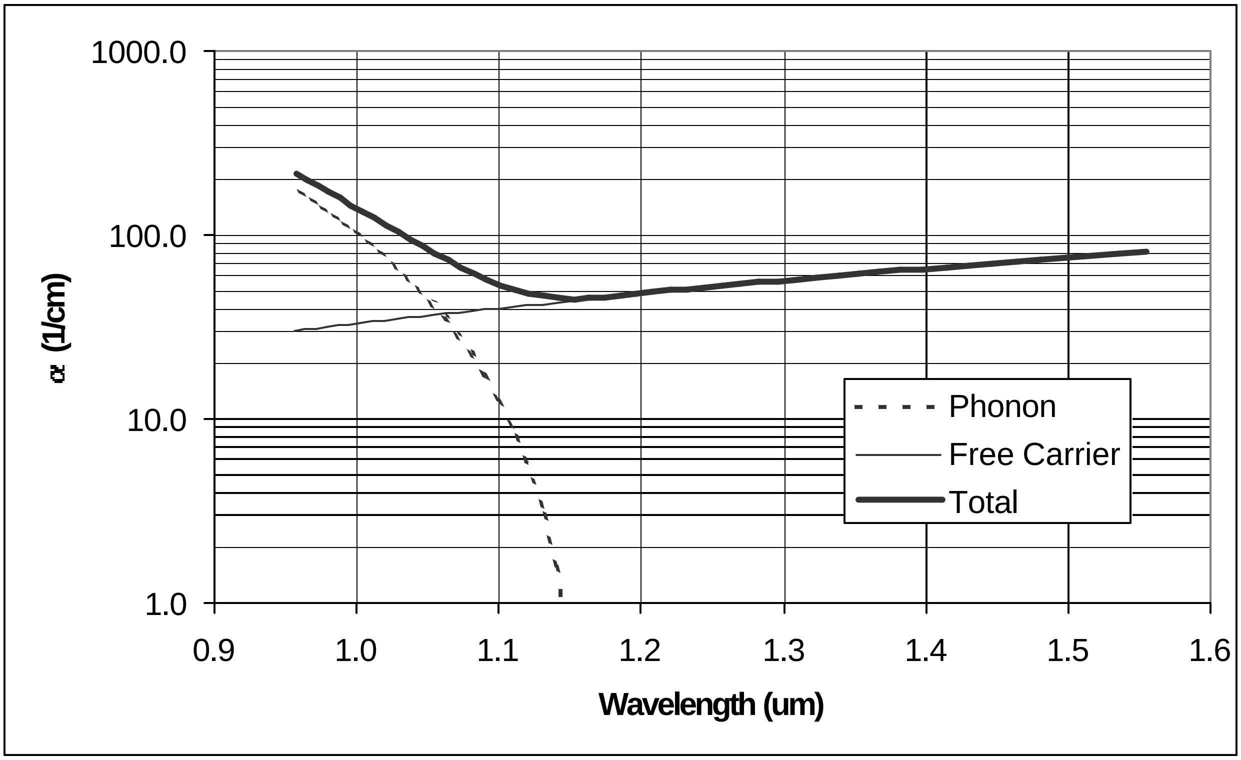

Figure 3 Absorption coefficient versus wavelength as derived from empirical formulas for a p dopant density of 1×10^{19} (1/cm^3).

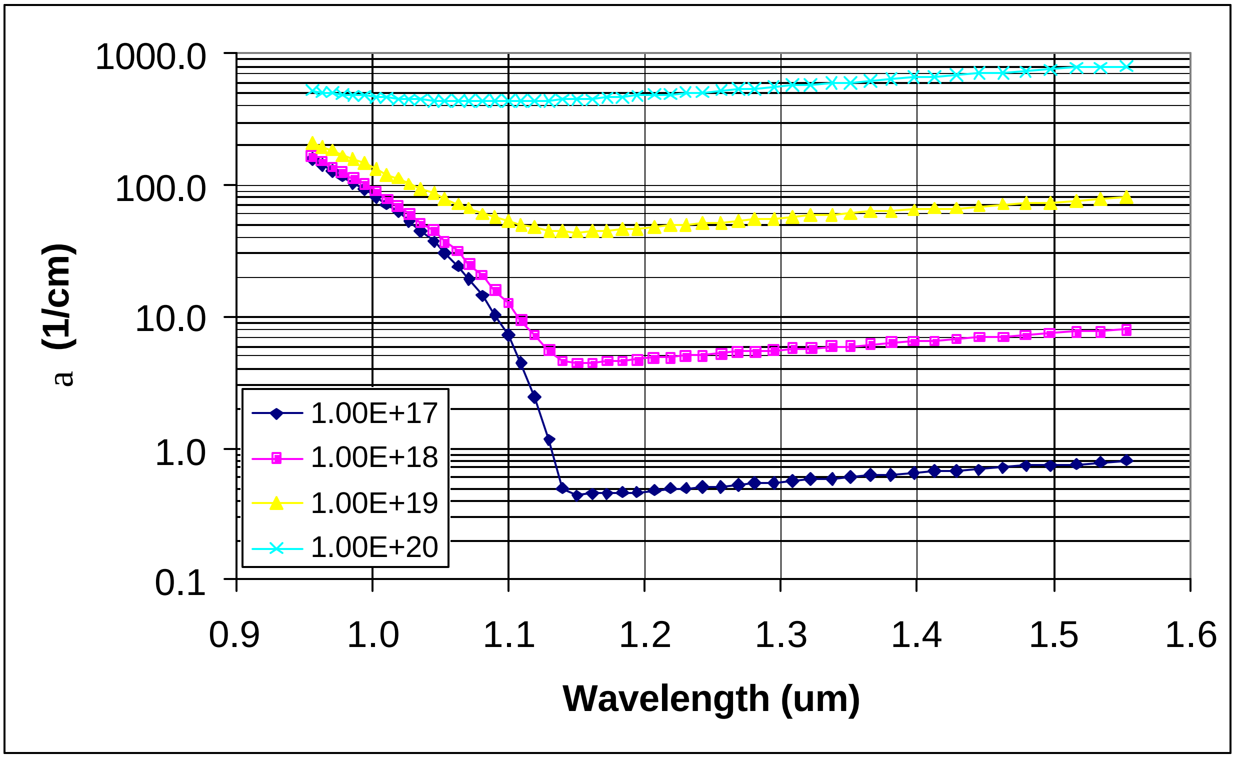

Figure 4 Absorption coefficient versus wavelength with p dopant level as a parameter.

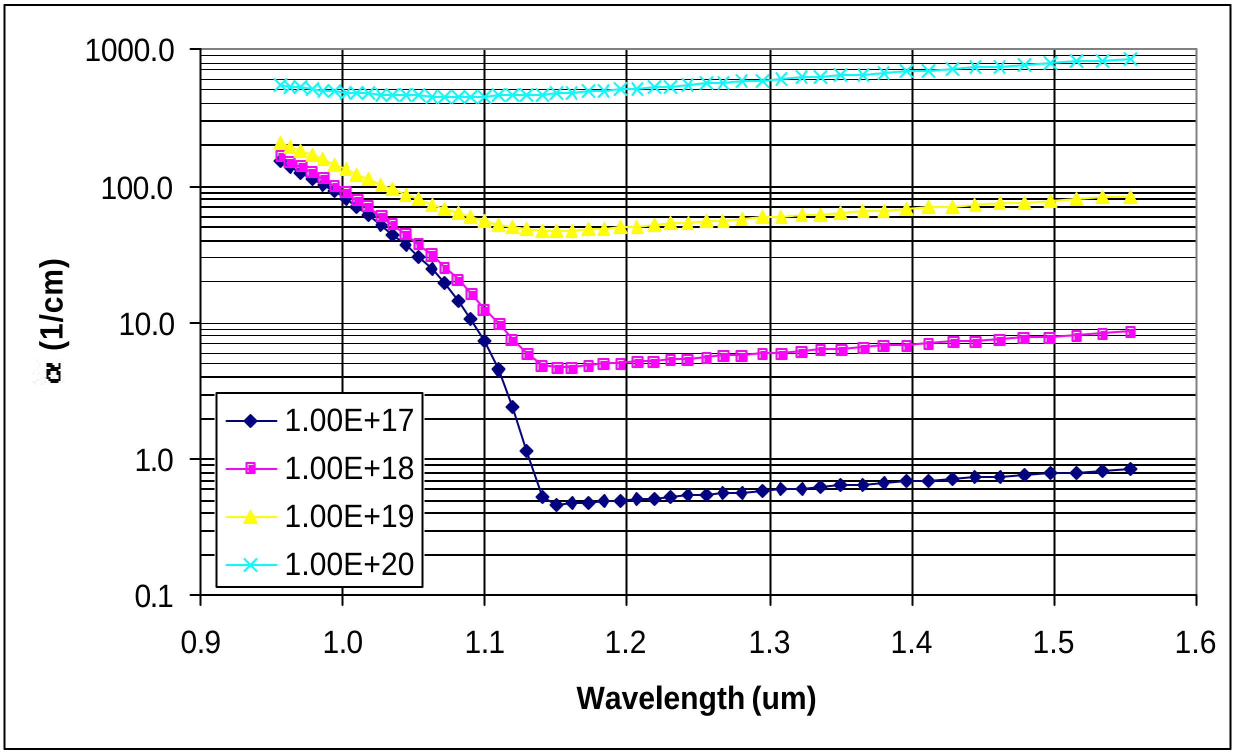

Figure 5 Absorption coefficient versus wavelength with n dopant level as a parameter.

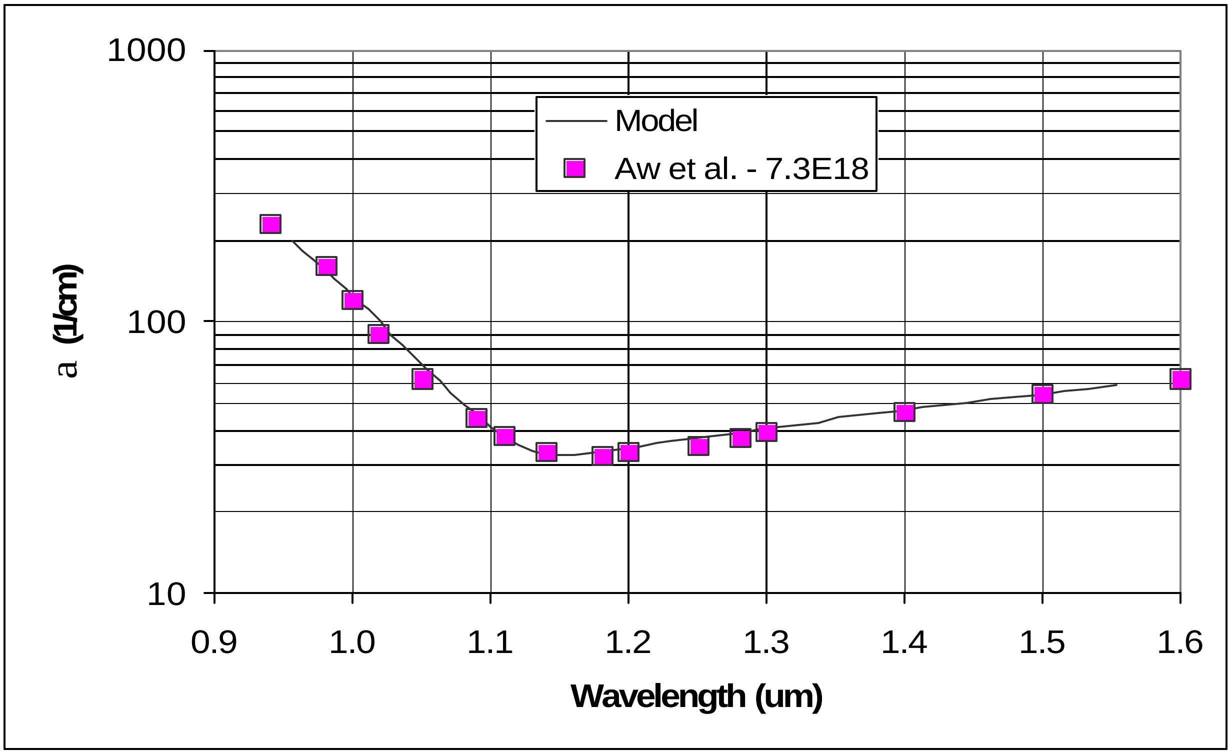

Figure 6 Example fit to Aw et al.

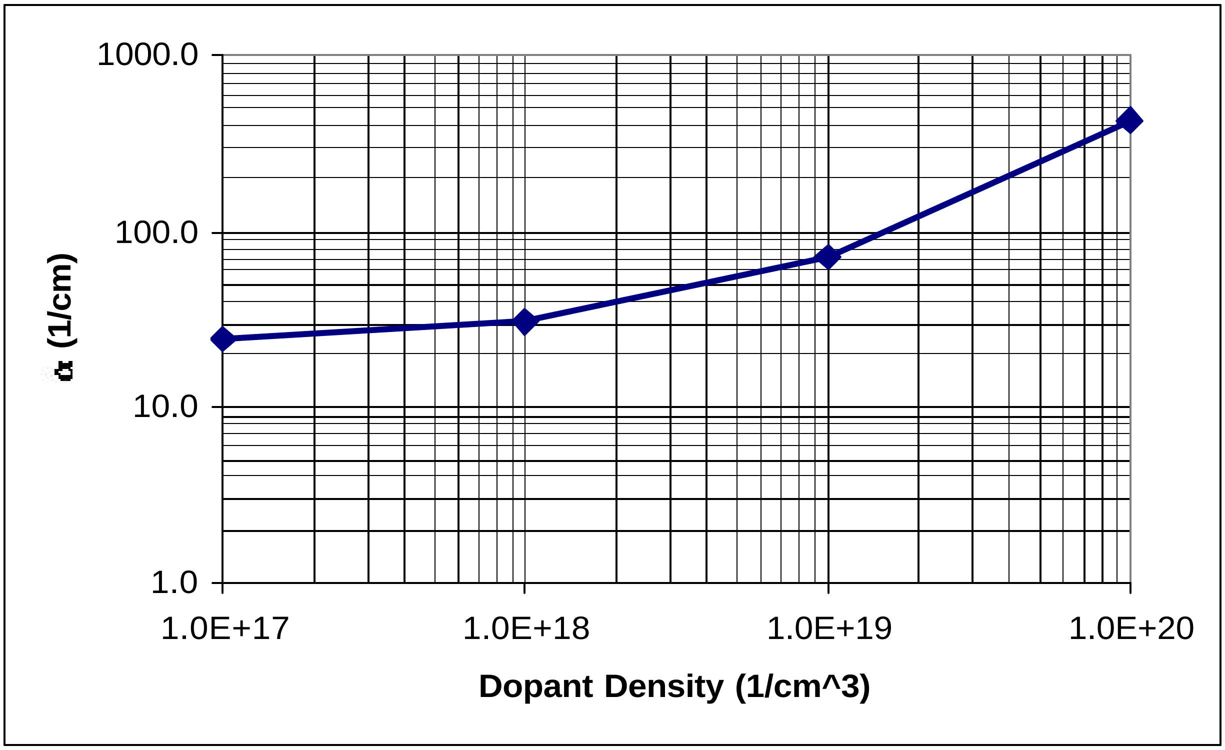

Figure 7 Absorption coefficient versus p dopant density for a wavelength of ~1.064 um.

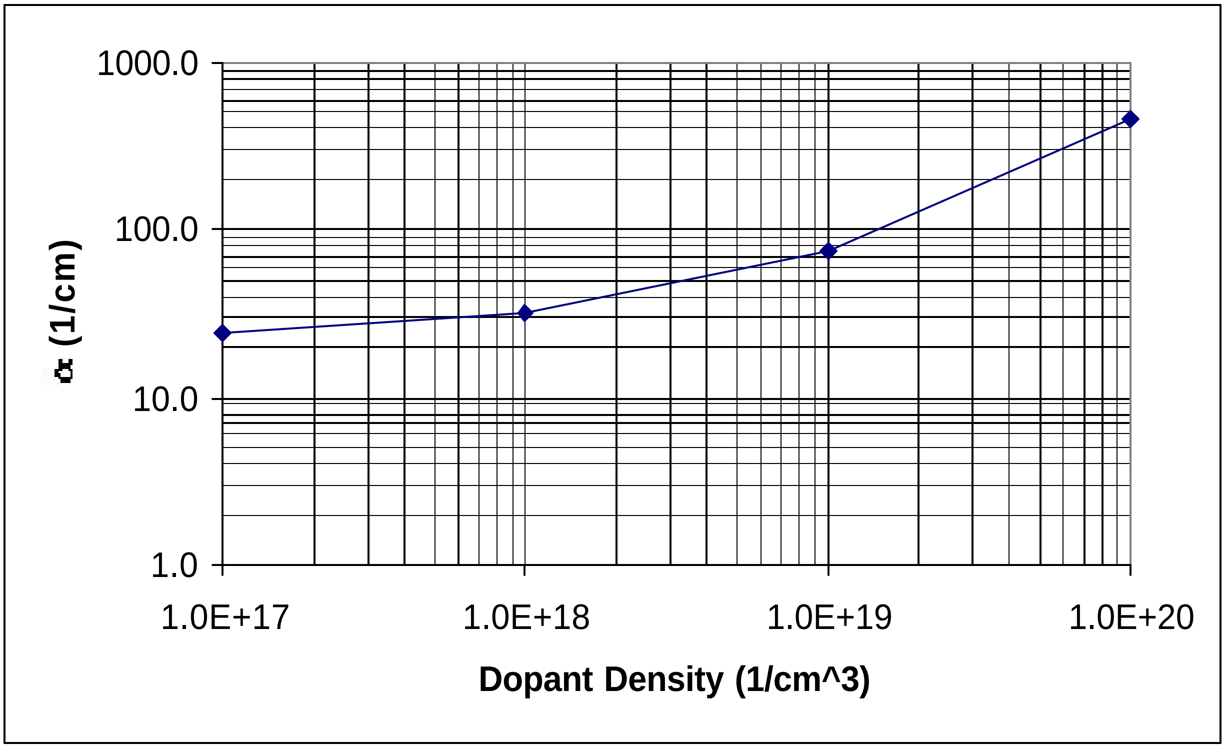

Figure 8 Absorption coefficient versus n dopant density for a wavelength of ~1.064 um.