Optical properties of amorphous thin-film MoGe

THESIS
submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
PHYSICS

Author : Daniëlle van Klink
Student ID : s1375458
Supervisor : Dr. Michiel de Dood
2nd corrector : Prof. dr. Jan Aarts

Leiden, The Netherlands, December 18, 2018
Optical properties of amorphous thin-film MoGe

Daniëlle van Klink

Huygens-Kamerlingh Onnes Laboratory, Leiden University
P.O. Box 9500, 2300 RA Leiden, The Netherlands

December 18, 2018

Abstract

An optimal design of a superconducting single photon detector depends on the optical properties of the superconducting material. Here we describe transmission and reflection measurements on thin-film amorphous MoGe deposited on fused silica (SiO$_2$) substrates and ellipsometry of thin amorphous MoGe films on Si(100) substrates. From the ellipsometry we find a simple relation between the dielectric constant $\epsilon$ and the thickness $d$ for film thicknesses between 5 and 30 nm. This simple relation entails a surprisingly strong dependence of the dielectric constant found in films that are much thicker than the electron mean free path ($\sim 0.5$ nm) derived from resistivity measurements in literature. Reflection and transmission measurements of thin-film MoGe on SiO$_2$ show similar thickness dependence. However, the roughness of the SiO$_2$ substrate has significant influence on the measurements for the thinner films ($\leq 15$ nm).
# Contents

1 Introduction \hspace{1cm} 7

2 Theory \hspace{1cm} 11
   2.1 Transmission through layered materials \hspace{1cm} 11
       2.1.1 Transmission and Reflection Coefficients \hspace{1cm} 13
       2.1.2 Multi-layer sample \hspace{1cm} 15
       2.1.3 Incoherent substrate \hspace{1cm} 17
       2.1.4 Transmission and Reflection of MoGe on SiO$_2$ \hspace{1cm} 19
   2.2 Ellipsometry \hspace{1cm} 20

3 Setup \hspace{1cm} 23
   3.1 Transmission and Reflection Setup \hspace{1cm} 23
   3.2 Samples \hspace{1cm} 24
   3.3 Calibration of the Transmission and Reflection Setup \hspace{1cm} 25

4 Results \hspace{1cm} 27
   4.1 Ellipsometry \hspace{1cm} 27
       4.1.1 Influence of the assumptions \hspace{1cm} 32
   4.2 Reflection and Transmission measurements \hspace{1cm} 34

5 Conclusion and Outlook \hspace{1cm} 41
Chapter 1

Introduction

Knowledge of the optical properties of thin-film amorphous molybdenum-germanium (MoGe) is important for the design of superconducting single-photon detectors (SSPD) based on this material. The first SSPD was developed in the group of Gregory Gol’tsman in 2001[1] using crystalline NbN as the superconductor. An SSPD consists of a thin and narrow (∼ 5 x 100 nm) meandering nanowire with a typical length of hundreds of micrometers. The wire is cooled below the superconducting critical temperature and a bias current close to the device critical current is applied. When a photon is absorbed in the nanowire becomes normal and produces a measurable voltage pulse. After a detection event the bias current is strongly reduced and the material cools down again and returns to its superconducting state[2]. SSPDs can be very efficient, fast and infrared (IR) sensitive (not necessarily all three at the same time) making them interesting for many applications[3].

The efficiency, ease of fabrication and reproducibility of SSPDs can be improved by using different materials for the superconducting nanowire. Current SSPDs made from crystalline materials (mostly NbN and NbTiN) have demonstrated detection efficiencies up to 80% [4, 5], while SSPDs based on amorphous superconductors show device efficiencies up to 93%[6]. In addition amorphous superconductors show different saturation of the detection efficiency as a function of bias current[7] when compared to crystalline superconductors. These observations hint at a possible different detection mechanism in SSPDs based on amorphous superconductors.

Before any electronic detection process starts, the photon needs to be absorbed by the material. Hence the dielectric constant $\epsilon$ is of utmost
importance. The Drude model[8] provides a direct link between the dielectric constant and the dc-conductivity \( \sigma = 1/\rho \) of the material. For amorphous and non-crystalline materials this conductivity is dominated by electron scattering due to disorder. Measurements of the resistance of a thin-film MoGe wire in Figure 1.1 show an increase of the wire resistance with decreasing temperature. These observations are consistent with Mooij’s empirical rule that predicts universal behavior for the temperature dependent resistivity of high resistivity materials with \( \rho > 150 \, \mu\Omega\text{cm}[9] \). For our MoGe nanowire we estimate \( \rho \approx 200 \, \mu\Omega\text{cm} \) using the known length, thickness and width of the wire. The observation of Mooij’s empirical rule can be linked to weak-localization theories[10] for strongly disordered thin-films.

Because the interfaces in a thin-film contribute to electron scattering, the conductivity \( \sigma \) is expected to depend on film thickness when the thickness becomes comparable to the electron mean free path. Hence, the Drude contribution to the dielectric constant depends on thickness, as do many other properties of disordered materials. It is well known that the critical temperature \( T_c \) of a disordered thin-film also depends on the thickness of the film[11]. A relation between the critical temperature and the resistivity was found by Testardi et. al.[12]. Combining these relations leads to a universal picture where all physical properties are controlled by disorder. At present, no such universal rule exists.

![Figure 1.1: Resistance measurement of a MoGe SSPD.](image)
The relation between $\epsilon$, $\rho$, $T_c$ and disorder as discussed above only holds when the energy of the absorbed photon is much larger than the superconducting energy gap $\Delta$. When we take the example of NbN the superconducting gap is given by $2\Delta \approx 3.9k_B T_c$ where $T_c = 13.3$ K ($2\Delta \approx 4.47$ meV). The energy of a photon with a wavelength in the visible part of the spectrum ($\lambda = 500$ nm, $\nu = 600$ THz) is $\hbar \omega = 2.48$ eV $\gg 2\Delta$. The energy of the absorbed photons is much higher than the superconducting gap and the effect of this gap on the dielectric constant becomes negligible. Kornelsen[13] shows that the ratio of optical absorption in the superconducting state and the normal state becomes 1 for photon energies $\hbar \omega \gg 2\Delta$. This tells us that measurements of optical absorption in the normal state are identical to measurements in the superconducting state. If we ignore the relatively weak temperature dependence of the resistivity of MoGe, measurements of the dielectric constant can be performed at room temperature.

In this thesis reflection and transmission measurements as well as ellipsometry are used on different thickness thin-film MoGe sample to find the relation between the dielectric constant and the thickness. Ellipsometry measures the change in polarization upon reflection from a thin-film and yields the thickness and the dielectric constant of the material by fitting a model to the data. This dielectric constant can then be used to calculate the absorption. Section 2.2 discusses the theory of ellipsometry. Section 4.1 shows the results of the ellipsometry and what this implies for the thickness dependence of the dielectric constant.

With the reflection and transmission measurements the absorption can be directly calculated via $A = 1 - R - T$ when scattering is ignored. The dielectric constant can again be found by fitting a model to the data. Sections 3.1 and 4.2 discuss the reflection and transmission measurements and the results. Section 3.2 discusses the samples used in the ellipsometry, transmission and reflection measurements. The reflection, transmission and absorption of the samples were calculated using the transfer matrices. Section 2.1 shows an elaborate explanation on how to utilize the transfer matrix principle and how to include the effect of thick substrates.
2.1 Transmission through layered materials

In this section we will discuss the optical transmission and reflection of a layered material. First, the amplitude transmission and reflection coefficients (Fresnel coefficients) of a single interface are calculated for both polarizations. Together, these coefficients define a 2x2 transfer matrix that forms the basis of a formalism for the reflection and transmission of multiple layers via matrix multiplication[14].

To obtain the Fresnel coefficients we consider a situation as sketched in Figure 2.1 where we choose a coordinate system such that the interface between the two media is the x-y plane ($z = 0$). We define the wave vector of the incident wave to have nonzero components along the x-axis and z-axis and limit the discussion to non-magnetic materials with magnetic permeability $\mu_1 = \mu_2 = 0$. The difference in optical properties is then indicated by the dielectric constants $\epsilon_1$ and $\epsilon_2$ of the two media. When the wave is incident from a medium with a real valued dielectric constant $\epsilon_1$, the wave vector is given by:

$$k = (k_x, 0, k_z)$$

The boundary conditions for electromagnetism require that the components of both the electric and magnetic field parallel to the interface are continuous:
For both polarizations these conditions are satisfied if the component of the wave vector along the interface is the same in both media:

\[ k_{1x} = k_{2x} = k_x = k_1 \sin \theta_1 = k_2 \sin \theta_2 \] (2.4)

where \( k_1 \) and \( k_2 \) are the length of the k-vector in medium 1 and 2 respectively. To obtain the z-component we use the dispersion relation:

\[ \varepsilon_1 \left( \frac{\omega}{c} \right)^2 = k_1^2 = k_x^2 + k_{1z}^2 \] (2.5)

Where \( \varepsilon_1 \) the electric permittivity or dielectric constant, which is given by:

\[ \varepsilon = (\eta + i\kappa)^2 \] (2.6)

Where \( \eta \) is the refractive index and \( \kappa \) the extinction coefficient. Formulating the problem in terms of \( \varepsilon \) allows for complex values of the optical constants and generalizes Snell’s law (Eq. 2.4) and the Fresnel coefficients for reflection from absorbing media.
2.1 Transmission through layered materials

(a) TE polarization

(b) TM polarization

Figure 2.2: Reflection and transmission of electromagnetic waves at an interface. In each figure the wave vector of two incoming waves are shown: one wave \((E_1^+, H_1^+)\) travels from left to right and reflects at the boundary, \(z = 0\). The second incoming wave \((E_2^-, H_2^-)\) travels from right to left. The superscripts \(+\) and \(−\) are used for waves propagating to the right and to the left, respectively. Image taken from [14].

2.1.1 Transmission and Reflection Coefficients

To calculate the transmission and reflection coefficients we distinguish two polarizations of waves; the transverse electric (TE) polarization or s-wave where the electric field is perpendicular to the scattering plane and the transverse magnetic (TM) polarization or p-wave where the magnetic field is perpendicular to the scattering plane. Figure 2.2 illustrates these two polarizations, where \(\epsilon_1\) should be real, while \(\epsilon_2\) can be complex.

**TE Polarization**

For TE polarization (see Fig. 2.2a) the vector \(E\) has only one component,

\[
E = (0, E, 0)
\]  

(2.7)

while the vector \(H\) has two components,

\[
H = (H_x, 0, H_z)
\]  

(2.8)

Using the boundary conditions and Maxwell’s equation we obtain the following equations:
\[ E_1^+ + E_1^- = E_2^+ + E_2^- \]  
\[ -\frac{k_{1z}c}{\omega} E_1^+ + \frac{k_{2z}c}{\omega} E_1^- = -\frac{k_{2z}c}{\omega} E_2^+ + \frac{k_{2z}c}{\omega} E_2^- \]

These equations written in matrix form look as follows:

\[
\begin{pmatrix} E_2^+ \\ E_2^- \end{pmatrix} = M^{(s)} \begin{pmatrix} E_1^+ \\ E_1^- \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 + \frac{k_{1z}}{k_{2z}} & 1 - \frac{k_{1z}}{k_{2z}} \\ 1 - \frac{k_{1z}}{k_{2z}} & 1 + \frac{k_{1z}}{k_{2z}} \end{pmatrix} \begin{pmatrix} E_1^+ \\ E_1^- \end{pmatrix}
\]

Where the matrix \( M^{(s)} \) is called the transfer matrix. This transfer matrix relates field amplitudes on different sides of the interface and can easily be expanded to a formalism that treats multiple interfaces.

For an incident wave from the left the E-field amplitude, \( E_1^+ \) corresponds to the incident wave, \( E_1^- \) to the reflected wave and \( E_2^+ \) to the transmitted wave. Hence \( E_2^- = 0 \) and using equation 2.11 the transmission and reflection coefficients are given by:

\[ r_s = \frac{E_1^-}{E_1^+} = -\frac{M^{(s)}_{21}}{M^{(s)}_{22}} = \frac{k_{1z} - k_{2z}}{k_{2z} + k_{1z}} \]  
\[ t_s = \frac{E_2^+}{E_1^+} = \frac{\text{det}M^{(s)}}{M^{(s)}_{22}} = \frac{2k_{1z}}{k_{2z} + k_{1z}} \]

The transmission and reflection are defined by:

\[ T_s = \frac{\text{Re}(k_{2z})}{\text{Re}(k_{1z})} |t_s|^2 \]  
\[ R_s = |r_s|^2 \]

where \( \text{Re}(k_{2z}) \) represents the real part of the wavevector \( k_{2z} \). The factor \( \text{Re}(k_{2z})/\text{Re}(k_{1z}) \) takes into account the difference in phase velocity in the two media.

**TM Polarization**

For the TM polarization (Fig. 2.2b) the \( H \) and \( E \) vector are given by:
2.1 Transmission through layered materials

\[ H = (0, H, 0) \]  \hspace{1cm} (2.16)
\[ E = (E_x, 0, E_z) \]  \hspace{1cm} (2.17)

The boundary conditions and Maxwell’s equation now give:

\[ H_1^+ + H_1^- = H_2^+ + H_2^- \]  \hspace{1cm} (2.18)
\[ \frac{k_{1z}}{\epsilon_1} H_1^+ - \frac{k_{1z}}{\epsilon_1} H_1^- = \frac{k_{2z}}{\epsilon_2} H_2^+ - \frac{k_{2z}}{\epsilon_2} H_2^- \]  \hspace{1cm} (2.19)

and the transfer matrix for TM polarization becomes:

\[
\begin{pmatrix} H_2^+ \\ H_2^- \end{pmatrix} = M^{(p)} \begin{pmatrix} H_1^+ \\ H_1^- \end{pmatrix} = \frac{1}{2} \left( \begin{array}{cc} \frac{\epsilon_2k_{1z}}{\epsilon_1k_{2z}} - \frac{\epsilon_1k_{2z}}{\epsilon_1k_{1z}} & 1 - \frac{\epsilon_2k_{1z}}{\epsilon_1k_{2z}} \\ 1 - \frac{\epsilon_2k_{1z}}{\epsilon_1k_{2z}} & 1 + \frac{\epsilon_2k_{1z}}{\epsilon_1k_{2z}} \end{array} \right) \begin{pmatrix} H_1^+ \\ H_1^- \end{pmatrix} \]  \hspace{1cm} (2.20)

The H-field amplitude, \( H_1^+ \) corresponds to the incident wave, \( H_1^- \) to the reflected wave and \( H_2^+ \) to the transmitted wave. In this case \( H_2^- = 0 \), so that the reflection and transmission coefficients are given by:

\[ r_p = \frac{H_1^-}{H_1^+} = -\frac{M_{21}^{(p)}}{M_{22}^{(p)}} = \frac{\epsilon_2k_{1z} - \epsilon_1k_{2z}}{\epsilon_2k_{1z} + \epsilon_1k_{2z}} \]  \hspace{1cm} (2.21)
\[ t_p = \frac{H_2^+}{H_1^+} = \frac{\det M^{(p)}}{M_{22}^{(p)}} = \frac{2\epsilon_2k_{1z}}{\epsilon_2k_{1z} + \epsilon_1k_{2z}} \]  \hspace{1cm} (2.22)

The transmission and reflection are given by:

\[ T_p = \frac{\epsilon_1 \text{Re}(k_{2z})}{\epsilon_2 \text{Re}(k_{1z})} |t_p|^2 \]  \hspace{1cm} (2.23)
\[ R_p = |r_p|^2 \]  \hspace{1cm} (2.24)

2.1.2 Multi-layer sample

We first consider a single slab of material with thickness \( d \) and permittivity \( \epsilon_2 \) between two semi-infinite media with permittivities \( \epsilon_1 \) and \( \epsilon_3 \). We assume that the electromagnetic parameters in the incoming and outgoing media are real, this need not be the case for the center medium. Using the
Figure 2.3: Transmission (red dotted line) and reflection (blue solid line) through a glass slab \((n = 1.45)\) with a thickness of 170\(\mu m\) embedded in air at wavelength 10\(\mu m\). The light is treated fully coherent resulting in interference between light waves reflected of the front and back surface of the slab.

The definition of the transfer matrices discussed above and the transfer matrix formalism from Chapter 1 of reference [14] the transfer matrix through the slab of material can be constructed via matrix multiplication:

\[
\begin{pmatrix}
E_3^+ \\
E_3^-
\end{pmatrix} = M_{slab}^{(s)} \begin{pmatrix}
E_1^+ \\
E_1^-
\end{pmatrix} = M^{12} \begin{pmatrix}
e^{i k_{2d}} & 0 \\
0 & e^{-i k_{2d}}
\end{pmatrix} M^{23} \begin{pmatrix}
E_1^+ \\
E_1^-
\end{pmatrix}
\]

(2.25)

Where \(M^{12}\) is the transfer matrix of the interface between the first and second material, \(M^{23}\) is the transfer matrix of the interface between the second and third material and the matrix \(P_2\) is defined as:

\[
P_2 = \begin{pmatrix}
e^{i k_{2d}} & 0 \\
0 & e^{-i k_{2d}}
\end{pmatrix}
\]

(2.26)

and represents the transfer matrix through a homogeneous medium with dielectric constant \(\epsilon_2\).

Figure 2.3 shows the calculation of the transmission and reflection through a SiO\(_2\) slab with thickness 170 \(\mu m\) and permittivity \(\epsilon = 2.1\) as a function of angle of incidence. Calculation are done at a wavelength of 10 \(\mu m\) to
2.1 Transmission through layered materials

clearly show the oscillations that arise due to constructive and destructive interference of the multiple reflected light beams.

The advantage of the transfer matrix formalism is that it can be straightforwardly extended to multilayers through matrix multiplication. For a system with \( n \) layers, the transfer matrix can be written as:

\[
\begin{pmatrix}
E_n^+ \\
E_n^-
\end{pmatrix} = M^{12}P_2M^{23}P_3 \ldots P_{n-1}M^{(n-1)n} \begin{pmatrix}
E_1^+ \\
E_1^-
\end{pmatrix}
\]  

(2.27)

2.1.3 Incoherent substrate

Figure 2.3 shows oscillations in the transmission and reflection calculated for perfectly coherent light. Such oscillations are not visible in the performed measurement since the coherence length of the light is not sufficient to measure this. The temporal coherence length of the light in our setup is set by the resolution of the spectrometer. For the spectrometer used in our research a resolution of 5nm is a realistic value. The coherence length \( L_{coh} \) is given by \( L_{coh} \sim \lambda^2/(n\Delta\lambda) \approx 130 \mu m \) for a wavelength of 1 \( \mu m \). Thus in our experiments we should treat the reflections from the back side of the 170 \( \mu m \) thick SiO\(_2\) substrate as incoherent.

The general case of a thick substrate with a reflective layer on both sides is treated by Harbecke[15]. The reflectivity of the layer on each side is calculated using a coherent sum, while the contributions of the layer on the bottom and top of the substrate are added incoherently. We consider light incident from medium \( a \) with a medium \( b \) underneath the substrate. The reflective layers at the two interfaces have Fresnel reflection and transmission coefficients \( r_{as} \) and \( t_{as} \) for the top layer and \( r_{sb} \) and \( t_{sb} \) for the bottom layer. These coefficients can be found using the transfer matrix formalism if the layer consists of more than a single interface. If we apply the transfer matrix formalism to the system with the thick substrate we find Fresnel amplitude coefficients.

\[
t_{ab} = \frac{t_{as}\phi_s t_{sb}}{1 - r_{sa}r_{sb}\phi_s^2}
\]

(2.28)

\[
r_{ab} = r_{as} + \frac{t_{as}\phi_s t_{sb}}{1 - r_{sa}r_{sb}\phi_s^2}
\]

(2.29)
Figure 2.4: Transmission (red dotted line) and reflection (blue solid line) through a glass slab \((n = 1.45)\) with a thickness of 170\(\mu m\) embedded in air at wavelength 10\(\mu m\). The light is treated incoherently in the propagation through the glass slab removing the oscillations that are visible in Fig. 2.3.

The factor \(\phi\) is the change in phase and amplitude that the light picks up while traveling through the substrate and is given by:

\[
\phi = \exp \left( i \frac{\omega}{c} \sqrt{\epsilon_s d_s} \right) = \exp \left( i \frac{\omega}{c} \eta_s d_s - \frac{\omega}{c} \kappa_s d_s \right) \tag{2.30}
\]

with \(d_s\) the thickness of the substrate. Up to now, we have merely rewritten the transmission and reflection coefficients of the system in terms of the transmission and reflection coefficients of the two thin films on both sides of the substrate. To add the contributions of the substrate incoherently we take the absolute value of the complex coefficients; and calculate the reflected and transmitted intensity as a function of the angle of incidence \(\theta_i\) as follows:

\[
R_{\text{incoh}} = |r_{as}|^2 + |t_{as} t_{sa} r_{sb}|^2 \frac{\exp \left( -4 \frac{\omega}{c} \kappa_s d_s \right)}{1 - |r_{sa} r_{sb}|^2 \exp \left( -4 \frac{\omega}{c} \kappa_s d_s \right)} \tag{2.31}
\]

\[
T_{\text{incoh}} = \frac{|t_{as} t_{sb}|^2 \exp \left( -2 \frac{\omega}{c} \kappa_s d_s \right) \text{Re}(\sqrt{\epsilon_s})}{1 - |r_{sa} r_{sb}|^2 \exp \left( -4 \frac{\omega}{c} \kappa_s d_s \right) \cos \theta_i} \tag{2.32}
\]
2.1 Transmission through layered materials

Figure 2.5: Simple illustration of the sample used in the transmission and reflection measurements. Measurements were performed with the light incident from the MoGe ('left') or SiO₂ ('right') side.

Figure 2.4 shows the transmission and reflection for a slab of glass with a thickness of 170 µm and a refractive index of 1.45. The calculations were performed using the formulas above. Comparing the coherent (Fig. 2.3) and incoherent calculation (Fig. 2.4) shows that the incoherent calculations follow the average of the oscillations in the coherent calculations, as expected.

2.1.4 Transmission and Reflection of MoGe on SiO₂

We now apply the formalism to a relevant geometry of a thin MoGe film on a thick glass substrate as shown in Figure 2.5. The MoGe layer has a thickness \(d\) and the SiO₂ substrate has a thickness of 170 µm. Measurements were performed with the light incident on either side of the sample. In order to calculate the reflection and transmission we combine the matrix theory (section 2.1.1) for a thin MoGe film with the incoherent theory given by equations 2.31 & 2.32. Because the incident and outgoing media are the same, the \(\text{Re}(\sqrt{\epsilon_s}) / \cos \theta_i\) term becomes 1 and vanishes. The exponential factors in Eqs. 2.31 and 2.32 that take into account the absorption vanish since \(\kappa_{SiO₂} = 0\). Thus the transmission and reflection when the light is incident on the MoGe ('left') side of the sample in given by:

\[
T_{MoGe} = \frac{|t_{13}t_{34}|^2}{1 - |r_{31}r_{34}|^2} \quad (2.33)
\]

\[
R_{MoGe} = |r_{13}|^2 + \frac{|t_{13}f_{31}r_{34}|^2}{1 - |r_{31}r_{34}|^2} \quad (2.34)
\]

While for light incident on the SiO₂ ('right') side one finds:
\[ T_{\text{SiO}_2} = \frac{|t_{43}t_{31}|^2}{1 - |r_{34}r_{31}|^2} \]  
(2.35)

\[ R_{\text{SiO}_2} = |r_{43}|^2 + \frac{|t_{43}r_{34}r_{31}|^2}{1 - |r_{34}r_{31}|^2} \]  
(2.36)

As can be seen time reversal symmetry imposes that \( T_{\text{MoGe}} = T_{\text{SiO}_2} \).

### 2.2 Ellipsometry

Ellipsometry measurements of MoGe on Silicon samples (section 3.2) were performed using a Woollam M2000 ellipsometer in the group of Pieter Kik at the College of Optics and Photonics (CREOL), University of Central Florida. This section describes the general idea of ellipsometry, but will not discuss details of the used setup.

Ellipsometry is a convenient and accurate technique for the measurement of the thickness and refractive index of thin-films on a surface. This technique utilizes the changes in polarization of light upon reflection\[16\]. Figure 2.6 shows a simplified schematic of an ellipsometry setup. Light from the source passes through the polarizer to ensure that linear polarized light arrives at the sample. The orientation of the polarizer at an angle \( \alpha \) gives both s- and p-polarization components to the light. The angle of incidence, \( \Phi \), is known and can be varied. After reflection a polarizer, oriented at an angle of \( \theta \), serves as an analyzer. It is customary in ellipsometry to express the ratio of the Fresnel coefficients as:

\[ \frac{r_p}{r_s} \equiv \tan \Psi e^{i\Delta} \]  
(2.37)

In the ellipsometer the analyzer and polarizer are rotated and the intensity as function of time is recorded. From this data the complex ratio \( r_p/r_s \) and the ellipsometer parameters \( \tan \Psi \) and \( e^{i\Delta} \) as a function of both angle and wavelength can be extracted. We use the CompleteEASE Software supplied with the ellipsometer to fit \( \Psi \) and \( \Delta \) and retrieve the optical parameters of the film.
Figure 2.6: Simplified schematic of an ellipsometry setup. The polarizer linearly polarizes the light. The analyzer and polarizer rotate continuously to detect the change in polarization due to reflection.
Setup

3.1 Transmission and Reflection Setup

Figure 3.1 shows the setup used for the transmission and reflection measurements. The light from a fiber coupled light source is directed through a polarizer and focused onto the sample that is mounted on a rotation stage. The transmitted or reflected light is collected by a lens and is analyzed by a fiber coupled spectrometer. Both the lens and spectrometer are mounted on a moveable arm.

As a light source a halogen lamp with a wavelength range of 360 to 2400 nm coupled to a 400 µm multimode fiber is used. A collimator lens (f = 50 mm) connected to the fiber creates a parallel beam that is polarized by passing through a polarizer. This polarizer can be rotated 360° and both the s- and p-polarizations can be chosen as well as any other polarization in between. After the polarizer the light travels through a lens (f = 75 mm) that focuses the light onto the sample (spot size ∼ 600 µm). The sample is illuminated by a halogen light source.

**Figure 3.1:** Schematic overview of the setup for the transmission and reflection measurements. A halogen light source illuminates the MoGe sample and the spectrometer analyzes the reflection or transmission.
mounted on a rotation stage that can be rotated 360°, so that the sample can be illuminated from all angles of incidence. After the transmission or reflection the light is collected by another lens (f = 150 mm) and coupled to a 400 µm multimode fiber using a fourth lens (f = 50 nm). The spectrum is analyzed by an Ocean Optics spectrometer, model USB2000+, which has a wavelength range from 525 to 1100 nm. All fibers that were used have a numerical aperture of 0.22.

The collection arm can be rotated such that either the reflected or transmitted light is collected. Figure 3.1 shows the configuration for transmission measurements. Due to the mechanical limitations of the system transmission measurements can be performed between -70° and 70° angles of incidence and reflection measurements between 25° and 80°. Measurements as function of angle were performed in steps of 0.5°, unless noted otherwise.

3.2 Samples

For the production of the samples a thin layer of Mo$_{0.71}$Ge$_{0.29}$ was deposited on a substrate at room temperature by sputtering from a composite target. Sputtering was done in an Argon atmosphere with a 1 kV potential and a distance of about 2-3 cm between the target and the substrate. The deposition rate on the substrate is approximately 5 nm per minute.

As a substrate we used fused silica (SiO$_2$) microscope cover slips with a diameter of 20 mm and a thickness of 170 µm. The deposition time was varied to produce seven samples with different thicknesses of the MoGe layer: 5, 10, 15, 20, 25, 30, 35 nm. Since the fused silica substrate is transparent and polished on both sides these samples can be used for reflection as well as transmission measurements. The films appear smooth and uniform to the eye.

Another four samples were produced with a silicon wafer substrate with MoGe layer thicknesses of 5, 10, 15 and 30 nm. The Si(100) wafer was polished on one side only and the MoGe was sputtered on the polished side. These samples were used in the ellipsometry measurements at UCF and in reflection measurements.
3.3 Calibration of the Transmission and Reflection Setup

To calibrate the setup described in section 3.1 we measured the reflection on a sample with a known dielectric constant. A measurement of the transmission was performed without a sample in the system to calibrate the transmission as function of wavelength.

To calibrate the reflection a (clean) silicon wafer, polished on only one side, was measured for both the s- and p-polarization. The measured reflection for s- and p-polarization is shown in Figure 3.2, where the top red curve shows the data for the s-polarization and the bottom blue curve the data for the p-polarization. The data as a function of angle is shown for a wavelength of 750 nm. The angle dependent Fresnel coefficient was fitted to the data in order to find the dielectric constant of silicon. The black dashed lines show a best fit to the data resulting in a value of $\eta = 3.53 \pm 0.01$ for the refractive index of the silicon wafer. In the analysis we have ignored the small imaginary part of the refractive index and a thin native oxide on the surface. Our best value is slightly below the literature value of $\epsilon = 3.7348 + 0.009i$ [17]. Moreover, for angles of incidence larger
than 60° we observe a slight decrease in reflectivity indicating that some light is lost at the largest angles of incidence.

The transmission was calibrated by measuring the ‘transmission’ of an empty sample holder. The sample with a diameter of 20 mm can be mounted on a ring with a inside diameter of 17 mm and an outside diameter of 20 mm. When the sample holder rotates to vary the angle of incidence the sample holder enters the optical path and influences the transmission. Figure 3.3 shows a drop in transmission at 66°. This indicates that the sample holder enters the optical path, from which we conclude that reliable transmission measurements can be done up to about 66°.
Chapter 4

Results

4.1 Ellipsometry

Ellipsometry measurements were performed using a Woollam M2000 ellipsometer at the College of Optics and Photonics (CREOL), University of Central Florida. Measurements were done for a wavelength range from 275 to 1700 nm and angles of incidence from 50° to 80° for four MoGe films on a Si(100) substrate. These samples have varying thickness of MoGe depending on the deposition time (see section 3.2). The data was fitted using the CompleteEASE software of the ellipsometer. In a first attempt we assumed that it would be sufficient to fit the data with a Drude model given by:

\[ \epsilon = \epsilon_{\infty} + \epsilon_{\text{Drude}}(\omega) = \epsilon_{\infty} - \frac{\tau}{\epsilon_0 \rho (\omega^2 \tau^2 + i\omega \tau)} \]  

(4.1)

where \( \rho = m^* m_e / (N q^2 \tau) \) is the resistivity in \( \Omega cm \). Here \( \tau \) is the scattering time and \( \epsilon_{\infty} \) is the dielectric constant for \( \omega \to \infty \). The fit parameters in the model are \( \rho, \tau, \epsilon_{\infty} \) and the film thickness \( d \). It is impossible to obtain an acceptable fit with this rather simple model. A much better fit can be obtained by adding a Lorentz oscillator term:

\[ \epsilon_{\text{Lorentz}}(\omega) = \frac{A \Gamma \omega_n}{\omega_n^2 - \omega^2 - i\omega \Gamma} \]  

(4.2)

where \( \omega_n = 2\pi v_n \) is the resonance frequency in \( rad s^{-1} \), \( \Gamma \) the width in \( rad s^{-1} \) and \( A \) a dimensionless amplitude. It should be noted that the frequency of the oscillator is close to the bandedge of the direct transition in silicon.
Table 4.1: Values of the fit parameters for the 4 Mo$_{0.71}$Ge$_{0.29}$ films on Si(100) derived from the ellipsometry.

<table>
<thead>
<tr>
<th>sample</th>
<th>d (nm)</th>
<th>$\rho$ ($\mu$Ωcm)</th>
<th>$\tau$ (fs)</th>
<th>A</th>
<th>$\hbar\Gamma$ (eV)</th>
<th>$\nu_n$ (THz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5nm</td>
<td>9.56</td>
<td>261</td>
<td>0.051</td>
<td>5.78</td>
<td>3.58</td>
<td>686.7</td>
</tr>
<tr>
<td>10nm</td>
<td>16.2</td>
<td>223</td>
<td>0.054</td>
<td>7.61</td>
<td>3.48</td>
<td>626.3</td>
</tr>
<tr>
<td>15nm</td>
<td>22.7</td>
<td>191</td>
<td>0.059</td>
<td>7.33</td>
<td>3.95</td>
<td>536.8</td>
</tr>
<tr>
<td>30nm</td>
<td>38.7</td>
<td>150</td>
<td>0.073</td>
<td>2.29</td>
<td>2.04</td>
<td>730.2</td>
</tr>
</tbody>
</table>

Figure 4.1: Fitted thickness from the ellipsometry measurements plotted against the predicted thickness of the samples from the deposition rate. The green line shows the linear relation $d_{\text{real}} = 1.2d_{\text{predict}} + 4.5$ nm. Note that this line does not cross the origin.

Samples with different thickness MoGe give different values for the fit parameters resulting in different values for the dielectric constant as can be see in Table 4.1 and Figure 4.2. Figure 4.1 shows the linear relation between the predicted and fitted thickness of the MoGe layers. Table 4.1 and Figure 4.2 suggest a dielectric constant that is dependent on the thickness of the film. This behavior is expected when the film thickness becomes comparable to the electron mean-free path in the Drude model, but data from Graybeal[18, 19] predicts a mean free path of $\sim 5$ Å, much smaller than the thicknesses of the samples in our study. Also, in the standard Drude model, the product of the resistivity and scattering time should be a constant, but this is not the case for these fit results. We note that the parameters of the Lorentz oscillator also depend on thickness, again this is not expected for a simple model.

Figure 4.3 illustrates how using a different value of the dielectric constant can influence the calculations of the reflection, transmission and thus
4.1 Ellipsometry

Figure 4.2: The real and imaginary part of the dielectric constant calculated with Eq. 4.1 & 4.2 using the different values of the fit parameters of the ellipsometry measurements (Table 4.1). The lines show the results for the 5 nm MoGe sample (black dotted line), the 10 nm MoGe samples (green dashed line), the 15 nm MoGe sample (red dashed-dotted line) and the 30 nm MoGe sample (blue solid line).

the absorption which is calculated by $A = 1 - R - T$. As an example the reflection, transmission and absorption of a 5 nm MoGe layer on a 170 µm SiO$_2$ substrate was calculated using two different values for the dielectric constant. These values were extracted from Figure 4.2 at a wavelength of 900 nm. This value of the wavelength is chosen since it is in the center of the range of the ellipsometry measurements and in the range of the reflection and transmission measurements. The blue solid lines in Figure 4.3 show the calculations performed with $\epsilon_a = 5.54 + 25.1i$, which is the value that corresponds to the curve for the 5 nm layer MoGe (Fig. 4.2) and the red dashed lines were calculated using $\epsilon_b = 2.57 + 36.9i$, which corresponds to the 15 nm curve (Fig. 4.2). At normal incidence the reflection calculated with $\epsilon_b$ is twice that of the calculated reflection with $\epsilon_a$ and the transmission of the $\epsilon_b$ calculation is 80% of the $\epsilon_a$ calculation. This results in a (relative) difference of $\sim 16\%$ in the calculation of the absorption.

Our next goal is to find a simple relation between the dielectric constant and the thickness of the thin film that can be used to predict the absorption of a realistic film as a function of film thickness. Even though we do not understand the physical origin of this thickness dependence, it is interesting to investigate the relation. Figure 4.2a shows that there is no simple straightforward thickness dependence in the real part of the dielectric constant, while Figure 4.2b shows that there might be a simple relation for the imaginary part especially when one looks at wavelengths...
Figure 4.3: Reflection, Transmission and Absorption calculated for a 5nm thick layer of MoGe on a SiO$_2$ slab at a wavelength of 900nm. The blue solid line shows the calculation using the value of the dielectric constant of $\epsilon = 5.54 + 25.1i$ and the red dashed line used $\epsilon = 2.57 + 36.9i$. 

(a) Reflection

(b) Transmission

(c) Absorption
4.1 Ellipsometry

Figure 4.4: Fitted scatter time against the predicted thickness. The red dashed line shows a linear fit through the 4 points giving $\tau = 0.0009 \ d_{\text{predict}} + 0.04575$ in fs. Note that the linear fit does not pass through the origin.

above 1200 nm. In order to find a relation we look a bit closer at how the Drude (eq. 4.1) and Lorentz (eq. 4.2) term behave with thickness. For the Lorentz term there seems to be no simple relation with thickness for both the real and imaginary part, but the Drude term appears to create an increase for the imaginary part of the dielectric constant and a decrease for the real part of the dielectric constant with increasing thickness. This can be understood by looking at the expression for the real and imaginary part of the Drude term and the behavior of the fit parameters with thickness. The Drude term from equation 4.1 can be split into a real and imaginary part as follows:

$$\text{Re}(\epsilon_{\text{Drude}}(\omega)) = \frac{-\tau}{\epsilon_0 \rho (1 + \omega^2 \tau^2)}$$

$$\text{Im}(\epsilon_{\text{Drude}}(\omega)) = \frac{1}{\epsilon_0 \rho \omega (1 + \omega^2 \tau^2)}$$

Where we used $\rho = m^* m_e / (Nq^2 \tau)$, the effective mass $m^*$ and the carrier concentration $N$ are independent of thickness.

Figure 4.4 shows the fitted scatter time $\tau$ as a function of the predicted thickness displaying a linear increase in scatter time with increasing thickness. The black line shows a linear fit through the scatter times. Although we only have four data points a linear relation between the thickness of the sample and the fitted scatter time appears to be an accurate description of the data. Since the mean free path of MoGe[18, 19] is much lower than the thicknesses of these samples it is not clear what causes this lin-
Results

Figure 4.5: The black solid curve shows the imaginary part of the dielectric constant calculated with the Drude and Lorentz term. The blue dashed-dotted curve shows the contribution from the Drude term and the red dashed curve shows the contribution from the Lorentz term.

ear relation. When we combine this linear relation, equation 4.4 and the fact that the imaginary part of the dielectric constant is dominated by the Drude term (Fig. 4.5), we conclude that the imaginary part of the dielectric constant increases linearly with thickness. Since the real part of the dielectric constant is an order of magnitude lower than the imaginary part we can neglect the real part in calculations of the optical properties. This reduces the equation for the dielectric constant to:

\[
\varepsilon(\omega) \approx i\varepsilon''(\omega, \tau) = \frac{iNq^2\tau}{\varepsilon_0m^*m_e\omega(1+\omega^2\tau^2)} \tag{4.5}
\]

We are interested in the wavelength range where \(\omega^2\tau^2 << 1\) and the scatter time in fs can be fitted as (Fig. 4.4) \(\tau = 0.0009d_{\text{predict}} + 0.04575\) where \(d_{\text{predict}}\) is the predicted thickness of the MoGe layer based on the deposition time. Combining all the arguments given above results in the following approximate expression for imaginary part of the dielectric constant:

\[
\varepsilon''(\omega, d) \approx \frac{Nq^2(0.0009d_{\text{predict}} + 0.04575) \times 10^{-15}}{\varepsilon_0m^*m_e\omega} \tag{4.6}
\]

4.1.1 Influence of the assumptions

In the process of deriving equation 4.6 we have made the assumptions that we could neglect the real part of the dielectric constant as well as the
contribution of the Lorentz oscillator. This section explores the influence of these assumptions on some absorption calculations.

Figure 4.6 shows the absorption as function of thickness calculated with three different values of the dielectric constant. The black dashed line shows the absorption calculated with a dielectric constant where we take all contributions of the Drude and Lorentz term into account. The red solid line is calculated with the real part of the dielectric constant set to zero and the blue dash-dot line is where we neglect the real part and the contribution of the Lorentz term. The calculations of the values for epsilon are performed with the fit values for the 5nm MoGe sample (Fig. 4.6a) and for the 30nm MoGe sample (Fig. 4.6b). As can be seen from the figures the calculations using the approximate value of the dielectric constant are accurate within 10%. Given the rather crude approximations that are made, this estimate is very reasonable. Interestingly the deviations for very thin films (d<10nm) relevant for SSPD design are much smaller than 10%, we hypothesize that this is due to the fact that the propagation phase is unimportant, i.e. the optics is well-described using the concept of surface impedance[20].

![Figure 4.6](image-url)

**Figure 4.6**: Calculated absorption of a MoGe layer on a SiO$_2$ substrate (section 3.2). Calculations are shown using the dielectric constant of the 5 nm film (left) and the 30 nm film (right). The black dashed curve shows the calculation with contributions from the Drude and Lorentz term. The red solid line shows the calculation with the real part set to zero. The blue dashed dotted line shows the calculation with only the Drude contribution to the imaginary part and the real part set to zero.
Figure 4.7: Transmission of a 15 nm MoGe layer on a SiO$_2$ substrate. The black crosses show the transmission with the light incident on the SiO$_2$ side and the red dots for when the light incident on the MoGe side. Calculation are performed with $\epsilon = 2.5 + 37i$. The blue solid line is the calculation where the thickness is set to 15 nm and the green dashed line is calculated with the thickness set to 22.6 nm as found in the ellipsometry with a sample with a similar deposition time.

4.2 Reflection and Transmission measurements

Reflection and transmission measurements were performed on samples with a thin MoGe film on a 170 µm SiO$_2$ substrate (section 3.2). The samples have a nominal thickness between 5 nm and 35 nm estimated from the deposition time and deposition rate. All thicknesses mentioned in this report are nominal values unless specified otherwise. Taking the results from the ellipsometry measurements fit (Table 4.1) we can calculate the reflection and transmission (eq. 2.31 & 2.32) of the samples and compare this to the measurements.

Figure 4.7 shows the measured transmission of a sample with a 15 nm thin MoGe film for both the s- and p-polarizations of light. The region from 0° to 90° shows the data for s-polarization and the region from 0° to -90° shows the data for p-polarization. This way of displaying the results provides a convenient way to fit the data and define a single fit function that calculates the s-polarized transmission for positive angles and the p-polarized transmission for negative angles. Thus the s- and p-polarized
4.2 Reflection and Transmission measurements

(a) Light incident on MoGe

(b) Light incident on SiO$_2$

**Figure 4.8:** Reflection of a 10 nm MoGe layer on a SiO$_2$ substrate. The black crosses show the reflection with the light incident on the SiO$_2$ side and the red dots for when the light incident on the MoGe side. Calculation are performed with $\epsilon = 6.04 + 31.1i$. The blue solid line is the calculation where the thickness is set to 10 nm and the green dashed line is calculated with the thickness set to 16.1 nm as found in the ellipsometry with a sample with a similar deposition time.

Data can be fitted simultaneously with the same fit parameters (dielectric constant and thickness) assuming that an uniform and amorphous film displays no birefringence.

Figure 4.7 shows the measured and calculated transmission of a sample with a 15 nm thin MoGe film. The red dots and black crosses show the measured transmission when light is incident from the MoGe side and SiO$_2$ side of the sample, respectively. The blue solid line shows the calculated transmission with a thickness of 15 nm for the MoGe layer and the green dashed line shows the calculation when the thickness is set to 22.6 nm, i.e. the thickness found in the ellipsometry for a sample with the same deposition time. Both curves were calculated with the value of the dielectric constant that was found in the ellipsometry measurements ($\epsilon = 2.5 + 37i$). The measured and calculated reflection of a 10 nm thin MoGe film sample can be seen in Figure 4.8, where the blue solid line is calculated with a thickness of 10 nm for the MoGe layer and the green dashed line for a thickness of 16.1 nm as found in the ellipsometry. Figure 4.8a shows the reflection when the light is incident on the MoGe side of the sample and Figure 4.8b shows the reflection when the light is incident on the substrate (SiO$_2$) side of the sample. These figures show that the calculations for the reflections and transmission are more accurate when the thickness used in the calculations is the thickness found in the ellip-
Results

sometry measurement rather than the predicted thickness based on the deposition rate. We see similar behavior for all the other samples.

However, these figures also show that the calculations with the values for the dielectric constant found in the ellipsometry do not agree with the measured transmission and reflection of the samples. This is most clearly visible in Fig. 4.8a for angles of incidence larger than 50°. To resolve this issue the reflection and transmission data were fit to the matrix formalism (eq. 2.31 & 2.32) with the dielectric constant and the thickness independent of the ellipsometry results where the real($\epsilon'$) and imaginary($\epsilon''$) part of the dielectric constant are separate fit parameters. Unfortunately it was not possible to draw any firm conclusions from this. As explained in Ref. [20] the product of the imaginary part of the dielectric constant and the thickness determines the absorption, which creates a strong anti-correlation between these fit parameters.

To avoid this issue the data was fit using the real and imaginary part of the dielectric constant as fit parameters, while keeping the thickness $d$ of the MoGe layer fixed. The thickness is fixed to the value that was found in the ellipsometry, since this is assumed to be the most accurate value for the thickness, judging from Figure 4.7 and the results from the other samples. It is important to note that this thickness is determined from measurements of MoGe on a Si substrate and not on a SiO$_2$ substrate.

Figures 4.9a and 4.10a show the results of this fit for the transmission data of a 5 nm and 10 nm MoGe layer on a SiO$_2$ substrate. For the 5 nm MoGe layer the value of the dielectric constant was found to be $\epsilon_{5nm} = 25.7 + 15.6i$ and for the 10 nm layer $\epsilon_{10nm} = 19.5 + 30.0i$ was found. While these curves fit the transmission data very nicely, figures 4.9b, 4.10b and 4.11 show that values for the dielectric constants extracted from fitting the transmission do not explain the measured reflection. There are several possible causes for this.

First, a closer inspection of the s-polarized reflection with light incident on the MoGe side of the sample (red dots and blue solid curve for positive angles) in Fig. 4.9b & 4.10b shows that the measured reflection for the 5 nm and 10 nm layers increases with angle, while the calculated reflection stays constant. In the data for the 25 nm layer of MoGe we observe a reflection that stays constant. The shape of the reflection curve can be significantly altered by assuming that we do not have a closed film of MoGe on the SiO$_2$ substrate. As a result we illuminate a mixture of bare and MoGe covered
4.2 Reflection and Transmission measurements

![Graphs](image)

(a) Transmission  
(b) Reflection

**Figure 4.9:** Transmission and reflection of a 5 nm MoGe layer on a SiO$_2$ substrate. The red dots show the signal when the light is incident on the MoGe side and the black crosses show the signal with light incident on the SiO$_2$ side. The blue solid line shows calculations with the light incident on the MoGe side and the green dashed line shows calculations with light incident on the SiO$_2$ side. Calculations are performed with $\epsilon = 25.7 + 15.6i$ and $d = 9.5$ nm.

SiO$_2$. This assumption can be justified as it is not unreasonable that the polished SiO$_2$ substrate has a roughness of about 15 nm. When a thicker layer of MoGe is sputtered on the sample we no longer observe these difficulties in the measurement which is consistent with the idea that closed films are formed when the deposited thickness exceeds surface roughness. This problem is not encountered when MoGe is sputtered onto a Si wafer, because the surface of the Si wafer is much smoother.

Second, a problem with fitting the results is that more than one combination of the real and imaginary part of the dielectric constant can describe the measured transmission. Typically this gives very bad fits for the reflection as shown in Figures 4.10c and 4.10d. An obvious solution would be to fit the reflection. Unfortunately, in our case that fit gives an even larger error.

Third, we seem to miss some signal in the reflection when we compare the measured and calculated reflection. This adds to the difficulties in fitting the reflection and transmission with the same dielectric constant.

Based on these results we conclude that the substrate, and in particular the surface roughness, plays an important role in the measured optical properties. More research is needed to fully resolve this issue. For in-
Figure 4.10: Transmission and reflection of a 10 nm MoGe layer on a SiO\textsubscript{2} substrate. The red dots show the signal when the light is incident on the MoGe side and the black crosses show the signal with light incident on the SiO\textsubscript{2} side. The blue solid line shows calculations with the light incident on the MoGe side and the green dashed line shows calculations with light incident on the SiO\textsubscript{2} side. Calculations are performed with $\epsilon = 19.5 + 29.9i$ for (a) and (b) and with $\epsilon = -27 + 19i$ for (c) and (d) and $d = 16.1$ nm.
4.2 Reflection and Transmission measurements

Figure 4.11: Reflection of a 25 nm MoGe layer on a SiO$_2$ substrate. The red dots show the signal when the light is incident on the MoGe side and the black crosses show the signal with light incident on the SiO$_2$ side. The blue solid line shows calculations with the light incident on the MoGe side and the green dashed line shows calculations with light incident on the SiO$_2$ side. Calculations are performed with $\epsilon = 19.7 + 46.5i$ and $d = 33.5$ nm.

A better description of the optical properties could be obtained if we allow the thin film to be birefringent. Without further sample characterization this simply adds fit parameters to the description and does not lead to more insight.
Chapter 5

Conclusion and Outlook

Ellipsometry measurements of thin-film MoGe on a Si wafer show that the dielectric constant of thin-film MoGe depends on the thickness. The frequency dependence of the dielectric constant can be well-approximated by a Drude model where the film scatter time increases with increasing thickness. This behavior is expected when the film thickness is comparable to the electron mean free path in the material (∼5Å). The thicknesses of the samples in our measurements range between 5 and 35 nm, which is much thicker than the electron mean free path. Hence, the physical origin of this thickness dependence of the dielectric constant remains unclear.

The reflection and transmission measurements of thin-film MoGe on SiO$_2$ substrates shows the importance of a smooth (enough) substrate when working with such thin layers. The measurements on the thinnest samples can only be explained if part of the surface is not covered with MoGe. For thicker films the measurements do not add more information than ellipsometry.

Calculations of the reflection and transmission were performed to predict the absorption of a thin MoGe layer in order to find the optimal thickness for an SSPD. We stress that in these calculations the thickness dependence of the dielectric constant should be taken into account to get an accurate picture.

The findings in this report raise questions to be answered in future research. Most prominently there is a big discrepancy between the thickness of the MoGe layer based on the deposition rate while sputtering and the thickness that is fitted by the ellipsometry measurements. As a first step
in future research the real thickness of these layers should be determined, e.g. by atomic force microscopy (AFM) measurements. Transmission electron microscopy (TEM) can be performed to find the thickness of a surface oxide on the MoGe layer if present.

When the thickness of the layers is confirmed, ellipsometry can be used to expand Figure 4.4 by measuring more samples with different thicknesses of the MoGe layer. It would be useful to look at both thicker and thinner samples. The thicker samples (up to $\sim$150 nm) can be used to determine the thickness where the dielectric constant no longer depends on the thickness. Samples with thinner MoGe layers, below 5nm, will show an increasing thickness dependence for the dielectric constant when the layer becomes comparable to the mean free path. As a final note it would be interesting to investigate if a different substrate and different deposition conditions influence the dielectric constant of the MoGe. If this is not the case the observed behavior is a universal rule for thin-film MoGe that awaits physical interpretation.
Bibliography


