Investigations into bulk absorption in silicon, and the dependence on temperature

A S Bell[1], J Steinlechner[1], S Rowan[1], J Hough[1], I Martin[1], J Komma[2], D Heinert[2], R Nawrodt[2] and J Degallaix[3]

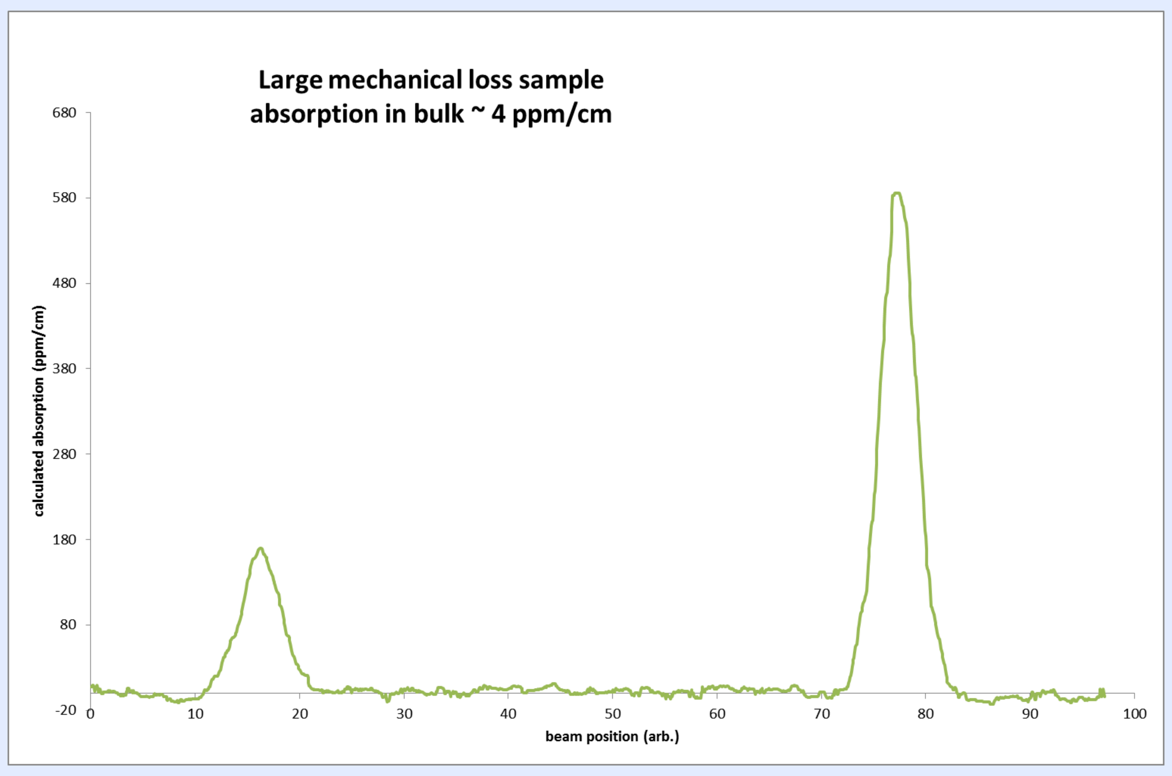
[1] Institute for Gravitational Research, SUPA, University of Glasgow, Glasgow, G12 8QQ

[2]Friedrich-Schiller-Universität Jena, Institut für Festkörperphysik, Helmholtzweg 5, D-07743 Jena

[3] Laboratoire des Matériaux Avancés, IN2P3/CNRS, Université de Lyon, 7 Avenue Pierre de Coubertin, F-69100 Villeurbanne, France

Introduction

Silicon continues to emerge as the leading contender for the test masses in future cryogenic interferometric gravitational wave detectors. Measurements have been made on a number of samples with losses that would be acceptable in proposed detectors. Current research continues towards a fuller understanding of the nature of optical loss in silicon, both at cryogenic temperatures and at room temperature. We have looked at the temperature dependence in the absorption in relatively highly doped samples. We confirm the behaviour of an initial reduction in absorption below room temperature which is reversed at lower temperatures. We attribute this behaviour to the reduction in carrier cross-section during the initial temperature decrease, which becomes dominated by the neutral dopant absorption as the carriers "freeze out".



Measurement of α versus temperature

Although knowledge of the room temperature absorption of silicon is useful, we are more interested in the behaviour at cryogenic temperatures, where the material will ultimately be used. We have look at the behaviour of relatively highly doped samples to help understand the various effects one might expect as the temperature is decreased and to use that knowledge to enable a determination of the purity levels required to allow operation in a future detector. Correlating the cryogenic absorption with room temperature absorption is likely to greatly speed up future work on qualification of material.

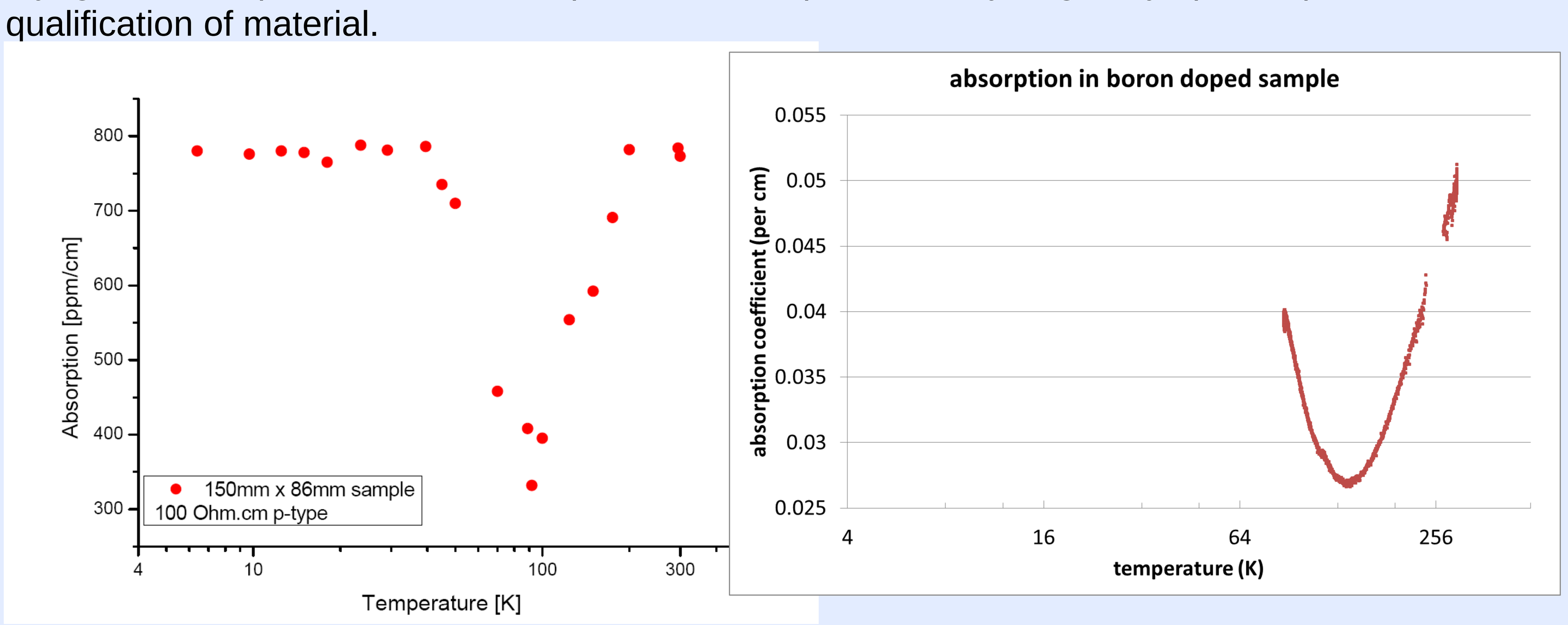


Figure 1. Absorption measurements on boron doped silicon wafers using calorimetric (left hand panel, Jena) and photothermal deflection (right hand panel, Glasgow) techniques.

Our interest was in the connection between the temperature of the minimum absorption and the dopant. If the absorption minimum was related to the ionisation energy of the dopant we might expect the minimum absorption point to shift to higher temperatures for higher ionisation energies.

Gallium has an ionisation energy in silicon of 70 meV. The figure below shows the absorption for a Ga doped wafer as a function of temperature, from 300 K down to 80K. The absorption is calculated from the deflection signal by dividing it by the signal one would expect for constant absorption.

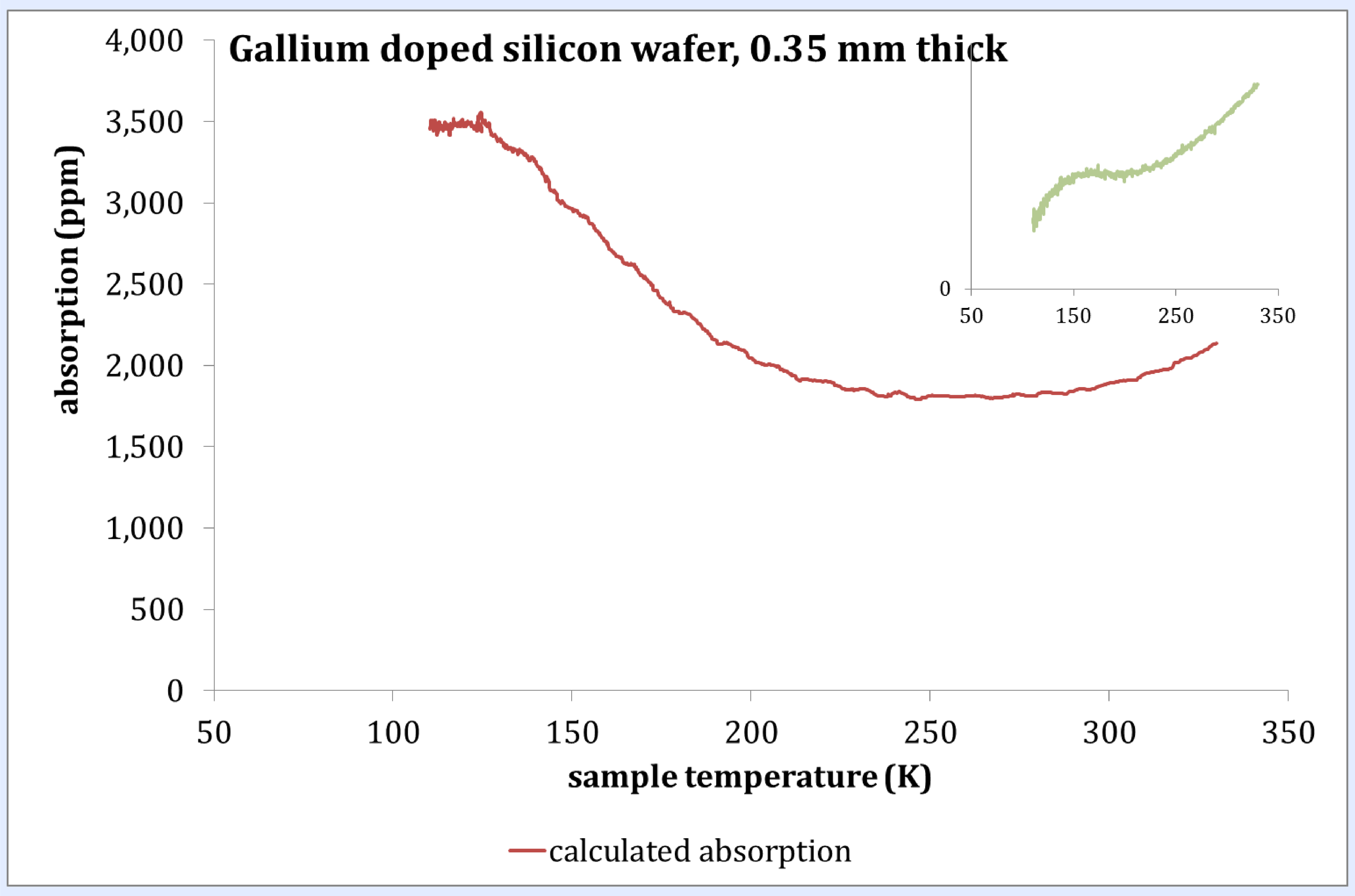


Figure 2. The calculated absorption from a Ga doped silicon wafer as a function of temperature. The inset in the graph shows the actual measured deflection signal.

Source of Absorption (α)

$$\alpha = \sum_i \sigma_i n_i$$

$$n_A = n_{A^0} + n_{A^*}$$

$$n_{A^*} = n_{free\ carriers}$$

$$n_{A^0}(T) = ?$$

$$n_{A^0}(T) = n_A(T) - n_{fc}(T)$$

$$\sigma_{A^0}(T) = ?$$

$$\sigma_{A^0}(T) \neq constant\ (?) \qquad \sigma_{FC}(T) = \frac{\sigma_0 T_0}{T}$$

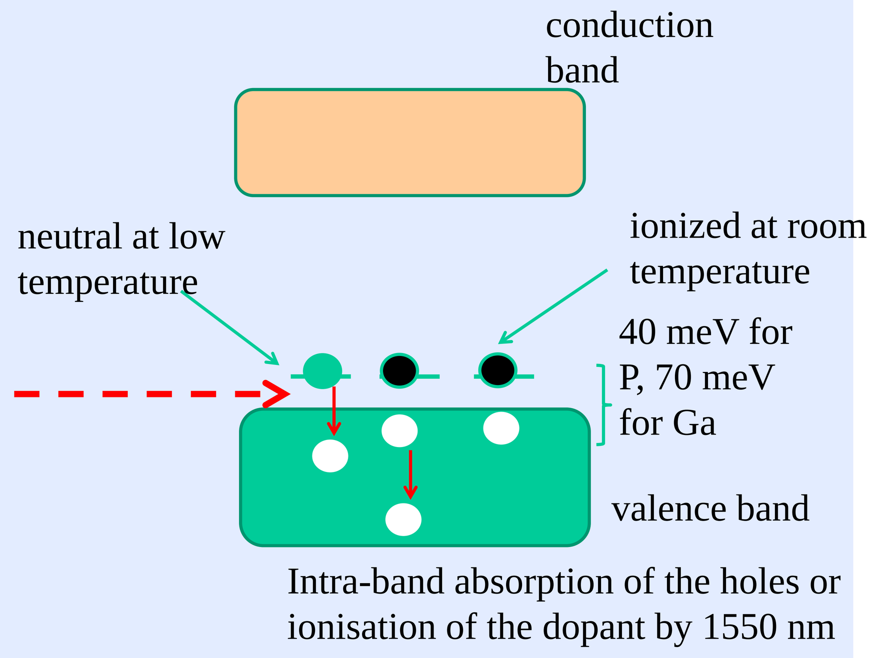


Figure 3. Representation of the energy levels of a p-doped semiconductor

At room temperature all the important semiconductor dopants are fully ionised. For group III dopants, this means there are free holes in the valence band that will absorb 1550 nm light. As the temperature drops, these holes recombine with ionised dopants to form neutral atoms. The neutral atoms also absorb 1550 nm - in the wings of the resonance line centered at the ionisation energy (18 μm for 70 meV, 31μm for 40 meV)

Model for Absorption

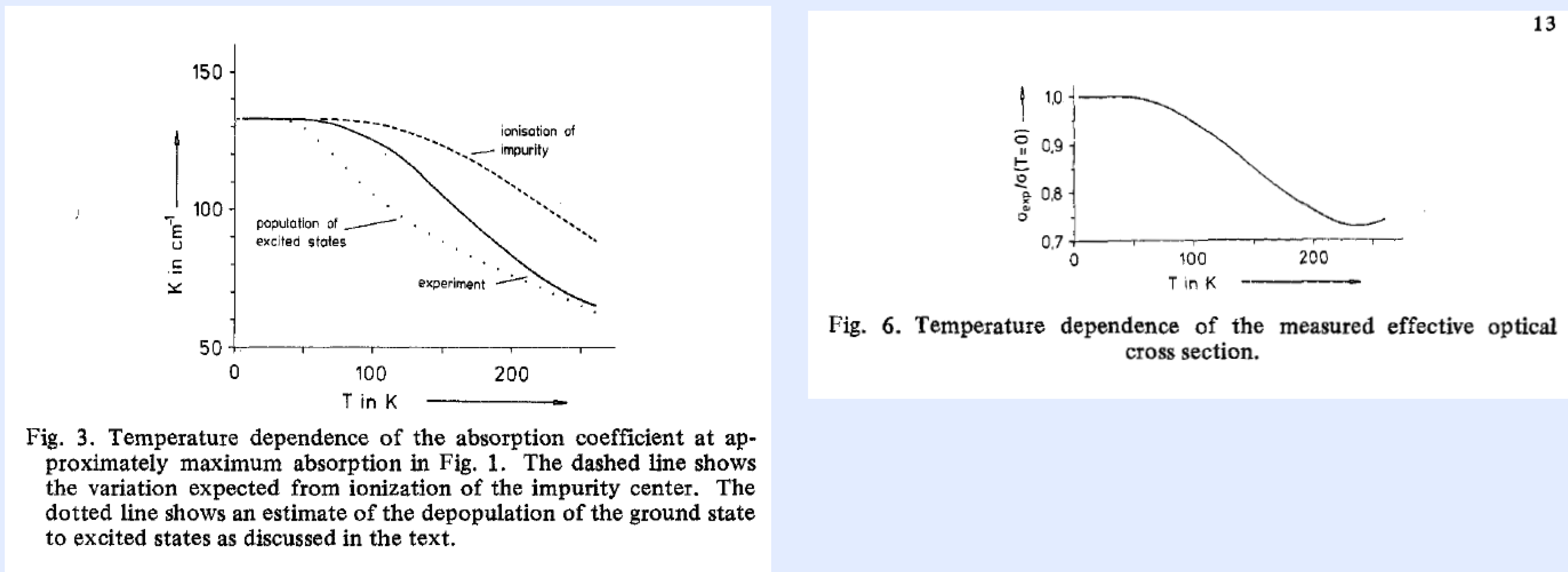


Figure 4. The right hand figure shows measured absorption from a Ga doped silicon wafer as a function of temperature. The left hand figure gives the change in neutral absorption cross section required to fit the data to the measured ion concentration

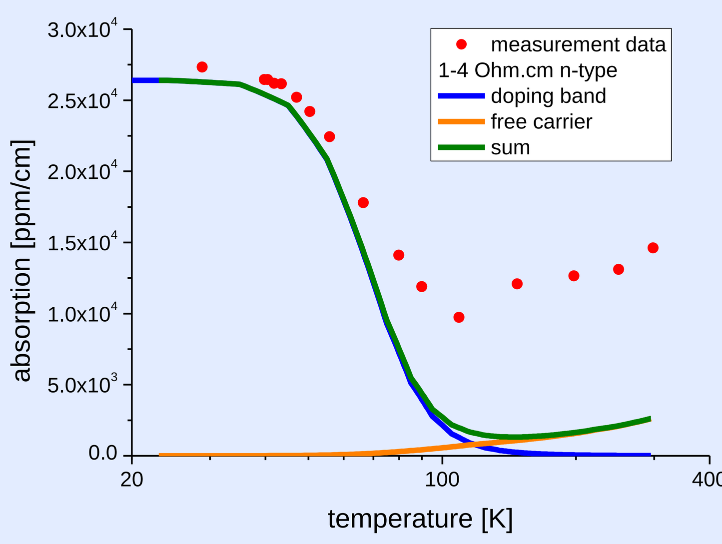
From Optical Absorption Of Gallium-doped Silicon, Wolfgang Hell, Reinhard Helbig, And Max J. Schulz, IEEE Transactions on Electron Devices, Vol. ED-27, No. 1, p10 JANUARY 1980

Measured at ~10 μm.

The work of Hell *et al*., looking at absorption around 10 microns, showed that there is a decrease in absorption as the dopant is ionised, however they report that the decrease is much faster with temperature than if only due to reduction in neutral dopants. They say that it can only be interpreted as a changed in the absorption cross-section of the neutral dopant with temperature.

The normal semiconductor dopants in silicon behave not unlike hydrogen atoms, in terms of their absorption spectra, but with a much reduced ionisation energy. Due to the high permittivity of silicon, dopants such as P, B & As all have ionisation energies of around 40 meV. This means that the fundamental absorption lines are in the far IR , around 30 μm.

Optical absorption studies on B and P doped samples showed that the absorption in both initially decreased as the temperature was dropped, but then increased. The minimum absorption for both materials appears to be around 100 K. The boron doped material increases to a level almost exactly equal to that at room temperature. The P doped material shows an absorption rise to significantly higher levels at temperatures below 100 K.



If one assumes a free carrier cross section that varies inversely with temperature below room temperature then the behaviour of the absorption can be modelled. The curve opposite assumes this as well as the dopant concentration and takes the neutral dopant cross section from J Geist, *Infrared absorption cross section of arsenic in silicon in the impurity band region of concentration* (APPLIED OPTICS / Vol. 28, No. 6 / 15 March 1989)

Figure 5. fit of absorption versus temperature for phosphorus doped silicon

Conclusion and future work

Recent measurements on Ga doped material lends weight to the hypothesis that the low temperature absorption is due to neutral dopants/contaminants. Further work is required to match up our knowledge of carrier density at room temperature with neutral dopant concentration and cross section at cryogenic temperatures.