Terahertz Emission and Absorption Characteristics of Silicon Containing Boron and Phosphorous Impurity Dopants and the Effect of Temperature

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Abstract— The emission and absorption characteristics of boron-doped and phosphorous-doped silicon at terahertz frequencies are investigated. Different doping concentrations are considered and individual terahertz optical transitions are identified. The effect of temperature is considered.

I. INTRODUCTION

Semiconductor lasers are gaining ever increasing importance in industrial applications and there have been sustained efforts over the past few years to develop a silicon based laser source. Such a device would represent a considerable advancement in optoelectronic technology since it would open the way for inexpensive monolithic integrated optical and electronic components. In the last two years there has been considerable interest in impurity dopants such as boron and phosphorous since it was demonstrated that such materials can show emission at THz frequencies [1]–[5]. In this paper we investigate the temperature dependence of these impurity transitions in order to estimate the most optimistic operating range of an impurity based silicon laser. These results should also be taken into account when designing potential THz silicon waveguides since both boron and phosphorous are commonly used to fabricate n- and p-type Ohmic contacts and could contribute to potential optical losses.

II. EXPERIMENTAL

Figure 1 shows two THz electroluminescence spectra for (a) a sample containing boron and (b) a sample containing phosphorous. Figure 1 shows several strong sharp spectral features in the electroluminescence spectrum which can be identified by comparison with absorption spectra in [7]. In the boron doped sample impurity based electroluminescence was extinguished at temperatures above 4.2 K, while in the case of the phosphorous doped sample, impurity based electroluminescence was observed up to about 40 K.

In order to further assess the effect of temperature and dopant concentration on these transitions, we performed a series of absorption measurements on bulk doped silicon
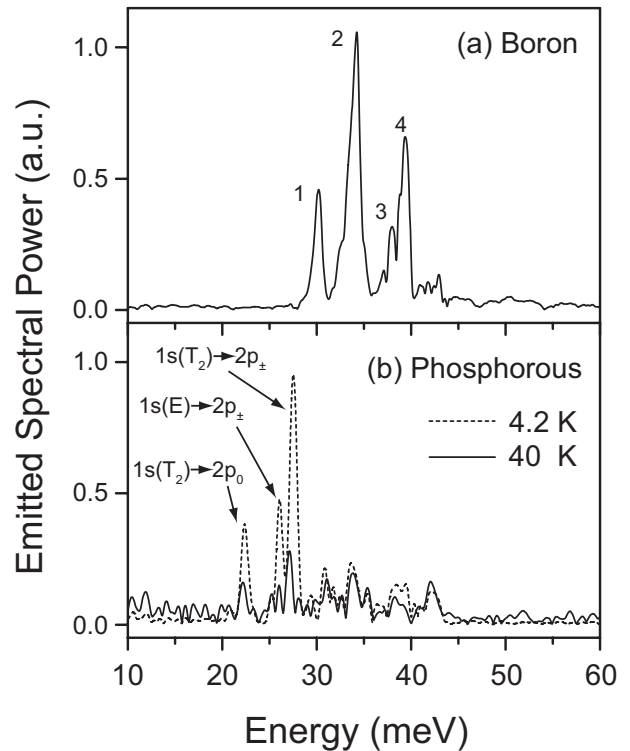

Fig. 1. THz electro-luminescence spectra for (a) a sample containing boron and (b) a sample containing phosphorous.

wafers. The details of each wafer are summarized in table I. Phosphorous doped wafers are labeled P1-P4 and boron doped wafers are labeled B1-B3. Samples were attached to the cold finger of a continuous flow cryostat allowing temperature tuning in the range 4.2 K ≤ T ≤ 300 K. Measurements were made using a Bruker 66VS spectrometer and a QMC helium cooled composite Si-bolometer detector.

The total absorption of each wafer was first measured as a

Wafer label	Resistivity (Ωcm)	Doping Conc. (cm^{-3})
P1	0.005-0.018	1×10^{19}
P2	0.04-0.14	2×10^{17}
P3	0.3	1.5×10^{16}
P4	2-9	5×10^{15}
B1	0.02	5×10^{18}
B2	0.05	1×10^{18}
B3	10-20	1×10^{15}

function of temperature. No transmitted signal was recorded through samples with dopant concentrations greater than 10^{18} cm^{-3}, and very little signal was recorded through the next highest dopant concentration. The behavior of the samples with dopant concentrations in the range $10^{15} - 10^{16}$ cm^{-3} is markedly different. Figure 2 shows the total absorption as a function of temperature of sample P3 (phosphorous) and sample B3 (boron), in the temperature range 4.2 K $\leq$ T $\leq$ 200 K. The total absorption for boron does not show a large change
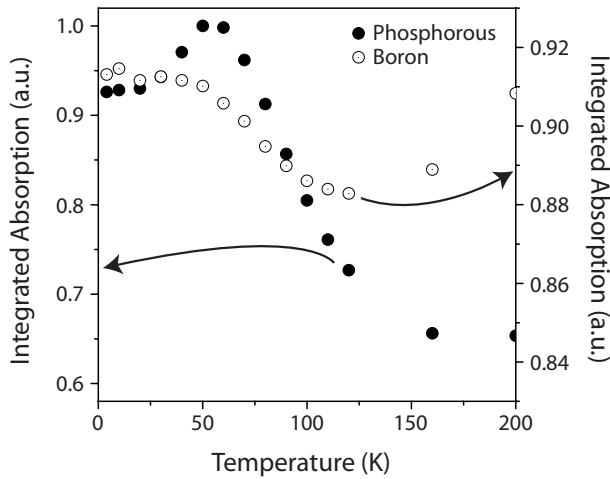

Fig. 2. Integrated absorption for samples P3 (phosphorous at 1.5×10^{16} cm^{-3}, and B3 (boron at 1×10^{15} cm^{-3}), in the spectral range 100-500 cm^{-1}.

over the temperature range in question. The maximum absorption is at 4.2 K and the absorption decreases with increasing temperature up to about 100 K. This behavior can be easily explained with reference to figure 3. At very low heat sink temperatures three very sharp absorption features can be observed between 30-40 meV. These correspond lines 1, 2, and 4 of the well-known $p_{3/2}$ series of Si(B) [7], [8]. As the heatsink temperature is raised between 4.2 K and 90 K, the transitions become progressively weaker, until they are finally extinguished around 100 K. This corresponds closely with a reduction in the total absorption up to 120 K as shown in figure 2. In contrast, the behavior of the phosphorous doped sample in figure 2 is quite different. Unlike the boron doped sample,
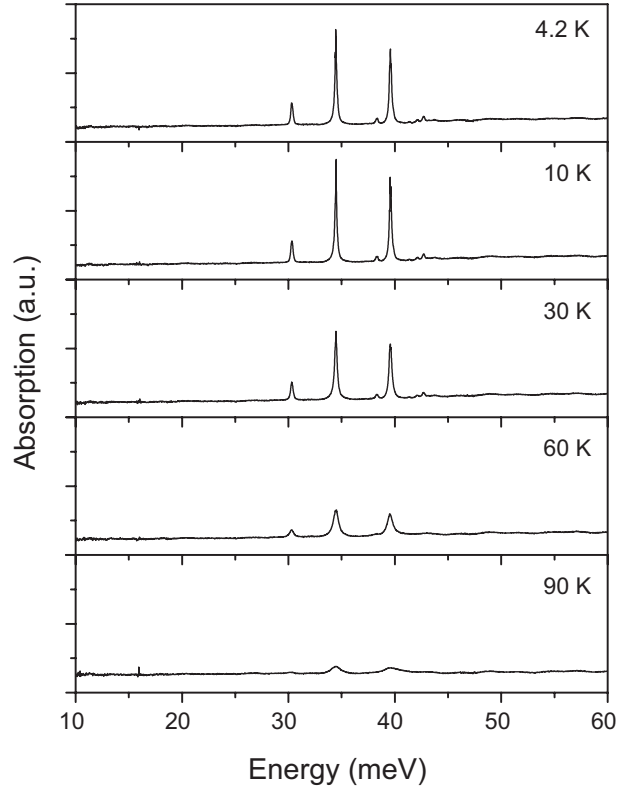

Fig. 3. THz absorption from boron doped silicon wafer B3 with temperature. The wafer has a resistivity of 10-20 Ωcm, giving a boron concentration of 1×10^{15} cm^{-3} .

the maximum absorption of the phosphorous doped sample is not at 4.2 K, and there is a local maximum in the absorption with temperature curve at 50 K. Close examination of figure 4 reveals that the absorption spectrum is dominated by three features in the range 30-45 meV at 4.2 K. These correspond to the $2p_0$, $2p_\pm$, and $3p_\pm$ Lyman series transitions to the ground state $1s(A_1)$ [7]. As the heatsink temperature is increased, a further set of thermally activated absorption lines appear between 20-30 meV. By considering the binding energies in [7], it is possible to show that these transitions are between the $2p_0$, $2p_\pm$ energy levels and the excited ground state $1s(T_1)$. These features reach maximum transition strength at 50 K, the local maximum of the relevant absorption with temperature curve in figure 2. It is from these additional thermally activated transitions that emission was observed in figure 1. Above 50 K, the strength of all the transitions begins to weaken until they are extinguished at around 100 K.

III. CONCLUSION

The temperature dependence of THz optical transitions from common dopants boron and phosphorous has been investigated. Sharp spectral features at THz frequencies resulting from these elements in single crystal silicon were best observed in samples with bulk dopant concentrations in the range $10^{15} - 10^{16}$ cm^{-3}. Above these dopant concentrations
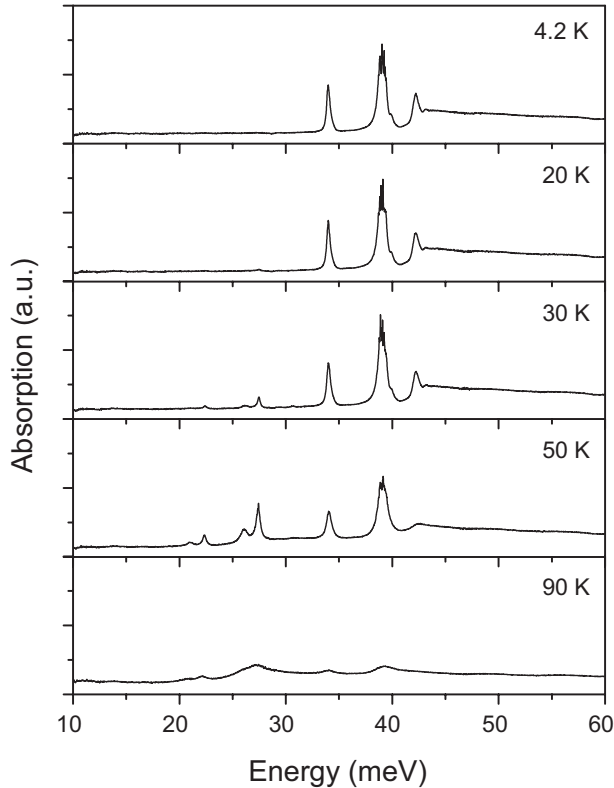
Fig. 4. THz absorption from phosphorous doped silicon wafer P3 with temperature. The wafer has a resistivity of 0.3 Ωcm, giving a phosphorous concentration of 1.5×10^{16} cm^{-3} .

the spectral features become very much broadened as the wavefunctions become delocalized. Below 10^{15} cm^{-3} the absorption becomes rapidly weaker and the spectral features become difficult to measure. The overall absorption due to boron in silicon decreases monotonically with increasing temperature in the temperature range 4.2 K $\leq$ T $\leq$ 100 K, as the transition strength of the boron lines becomes weaker and the transitions are eventually extinguished. The overall absorption due to phosphorous in silicon exhibits a local maximum at 50 K and then decreases with increasing temperature up to 100 K. This local maximum corresponds with the observation of thermally activated transition lines which are not observed at lower temperatures. In each case the exact transitions have been identified.

These results are important and need to be taken into account when designing potential THz silicon waveguides since both boron and phosphorous are commonly used to realize n- and p-type Ohmic contacts and will contribute to potential losses. The measured temperature dependence of these transitions also shows that the most optimistic operating range of an impurity based laser is 4.2 K $\leq$ T $\leq$ 90 K. This represents an ideal passive device with no current flowing. In a real device with current flowing and associated Joule heating the actual operating range is likely to be much narrower and it is unlikely such a device would have a maximum operating temperature above 40 K as in figure 1. This is quite consistent with the value quoted in [9].

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