

Determination of the Band Gap of Silicon
by Optical Absorption Via Power Transmission as a
Function of Wavelength

PH360 – Section 012

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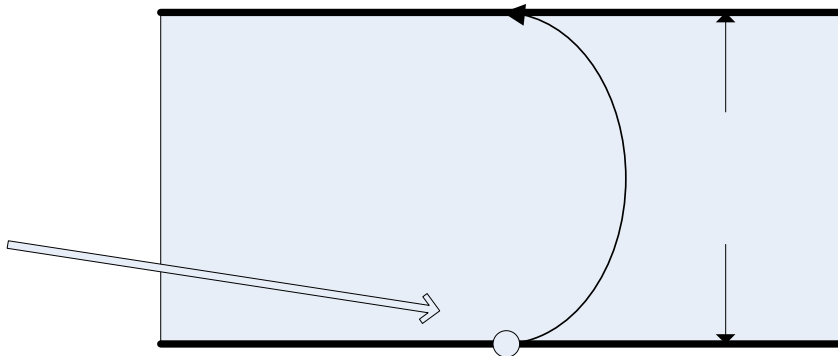
Purpose:

The purpose of this experiment was to determine the band gap of silicon by measuring its optical absorption. Using a silicon wafer, the photon absorption was to be noted at varying energy levels by measuring a percent transmission versus wavelength. By identifying the wavelength and subsequent energy associated with the transition between majority transmission and absorption, the band gap of the material could be identified.

Theory:

One of the various ways that electrons can be excited from the valence band to the conduction band is through photon absorption. This behavior is very similar to electron excitation in isolated atoms, where an entering photon excites an electron to a higher energy level. It is important to note that this behavior in isolated atoms only occurs when the photon energy is exactly equal to the difference between electron energy levels.

Figure 1: Photon Absorption in Isolated Atoms



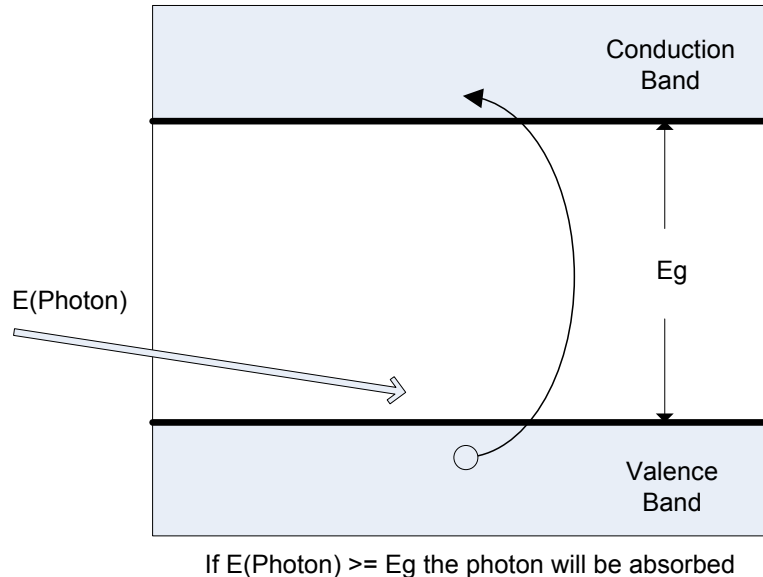
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Or mathematically speaking, absorption in isolated atoms occurs when:

$$E_{\text{Photon}} = \Delta E_{\text{IsolatedEnergyLevels}} \quad (1)$$

Although photon absorption in a semiconductor operates in the same manner, it occurs when the photon energy is at least the difference between the valence band and the conduction band, rather than when exactly equal to. Essentially, an electron in the valence band can be excited to the conduction band when the incoming photon energy is equal to or greater than the band gap energy. This can be seen in the diagram on the following page.

Figure 2: Photon Absorption in Semiconductors



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Once again, absorption can be represented mathematically:

$$E_{\text{Photon}} \geq E_G \quad (2)$$

Knowing this relationship, we can derive an equation for the wavelengths of light that would be absorbed by the material. This can be accomplished by applying the equation for the energy of a photon:

$$E_{\text{Photon}} = \frac{hc}{\lambda} \quad (3)$$

$$\lambda \leq \frac{hc}{E_G} \quad (4)$$

At this point we can define a cutoff wavelength, the longest wavelength that will still be absorbed by the material. Slightly modifying equation (4) we see:

$$\lambda_{\text{Cutoff}} = \frac{hc}{E_G} \quad (5)$$

$$E_G (\text{eV}) = \frac{1240 (\text{eV} \cdot \text{nm})}{\lambda_{\text{Cutoff}} (\text{nm})} \quad (6)$$

By monitoring the transmission of the light through the material as a function of the wavelength, the cutoff wavelength can be determined. Its presence should be somewhat obvious, as its occurrence is marked by the abrupt change in light transmission through the wafer.

To determine the light transmission through the material, a monochromator must be employed. Using a light source with many wavelengths, or “broad band”, a wide variety of wavelengths can be filtered with the monochromator. A power meter on the exit slit of the monochromator can be used to record the power both with and without the absorbing wafer in front of the light source; this ratio can then be used to calculate the percent transmission:

$$\% \text{ Transmission} = \left(\frac{Power_{WithAbsorber}}{Power_{WithoutAbsorber}} \right) \times 100\% \quad (7)$$

To successfully detect the wavelength range containing the cutoff for Silicon, a Germanium detector must be used in the optical power meter.

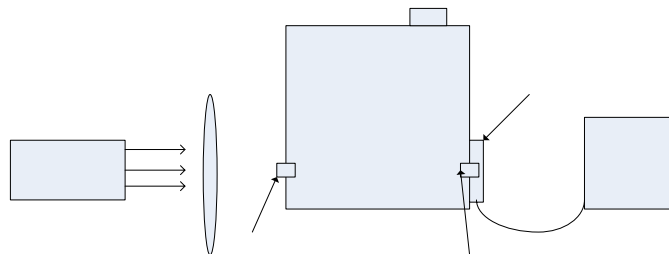
Equipment List:

- A Silicon wafer
- Sciencetech Model 9030 monochromator
- 55W quartz halogen light source
- Newport model 1830C/940 optical power meter
- Germanium detector

Procedure:

This particular experimental setup makes use of manual wavelength settings and power meter readings. It is important to note that the wavelength dial on the monochromator is exactly one half that of the actual transmitted light. Additionally, it can be assumed that the power readings are only accurate to roughly three significant figures.

Figure 3: Experimental Setup



Power readings were to be taken from 800nm to 1400nm in 10nm steps (or 400 to 700 on the monochromator dial), with a data point both with and without the silicon wafer covering the entrance slit. These two values could then be used in conjunction with equation (7) to create a graph of wavelength versus percent transmission. Visually examining the resulting curve, the transition period could be identified.

Data:

Table 1: Power Readings With and Without Absorbing Silicon

Dial	λ (nm)	Power w/ Si (nW)	Power w/o Si (nW)
400	800	6.44	338
405	810	6.42	334
410	820	6.46	332
415	830	6.53	338
420	840	6.63	357
425	850	6.76	367
430	860	6.96	376
435	870	7.19	385
440	880	7.45	384
445	890	7.78	391
450	900	8.10	402
455	910	8.51	408
460	920	8.98	415
465	930	9.74	423
470	940	10.6	417
475	950	12.4	423
480	960	15.0	431
485	970	19.5	432
490	980	26.5	440
495	990	42.0	490
500	1000	62.6	525
505	1010	78.7	480
510	1020	102	462
515	1030	137	456
520	1040	167	454
525	1050	203	454
530	1060	236	455
535	1070	257	455
540	1080	273	456
545	1090	290	456
550	1100	302	457
555	1110	309	457

560	1120	320	455
565	1130	323	456
570	1140	327	456
575	1150	332	456
580	1160	334	457
585	1170	336	456
590	1180	335	453
595	1190	337	452
600	1200	333	449
605	1210	330	448
610	1220	328	444
615	1230	325	440
620	1240	322	435
625	1250	320	434
630	1260	315	431
635	1270	312	426
640	1280	308	423
645	1290	305	419
650	1300	303	414
655	1310	299	408
660	1320	295	404
665	1330	292	401
670	1340	285	393
675	1350	280	385
680	1360	277	382
685	1370	273	378
690	1380	266	370
695	1390	265	365
700	1400	260	360

Results:

The resulting power data was applied to equation (7), producing a set of transmission percentages corresponding to the wavelengths of light supplied.

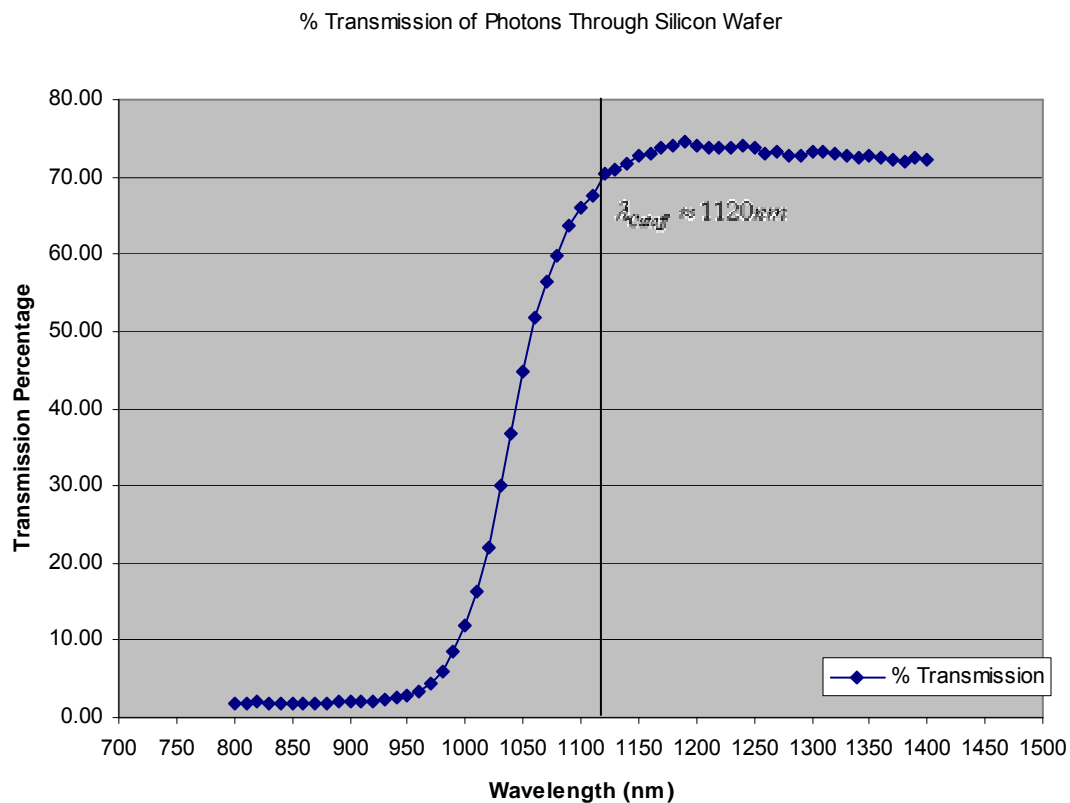
Table 2: Transmission Percentages of Silicon

λ (nm)	Transmission %
800	1.91
810	1.92
820	1.95
830	1.93
840	1.86
850	1.84
860	1.85

870	1.87
880	1.94
890	1.99
900	2.01
910	2.09
920	2.16
930	2.30
940	2.54
950	2.93
960	3.48
970	4.51
980	6.02
990	8.57
1000	11.92
1010	16.40
1020	22.08
1030	30.04
1040	36.78
1050	44.71
1060	51.87
1070	56.48
1080	59.87
1090	63.60
1100	66.08
1110	67.61
1120	70.33
1130	70.83
1140	71.71
1150	72.81
1160	73.09
1170	73.68
1180	73.95
1190	74.56
1200	74.16
1210	73.66
1220	73.87
1230	73.86
1240	74.02
1250	73.73
1260	73.09
1270	73.24
1280	72.81
1290	72.79
1300	73.19
1310	73.28
1320	73.02
1330	72.82

1340	72.52
1350	72.73
1360	72.51
1370	72.22
1380	71.89
1390	72.60
1400	72.22

Graph 1: Transmission Percentage Versus Wavelength



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As the wavelengths increase, the associated photon energies actually decrease, as per equation (3). This indicates that the cutoff wavelength is the shortest before the abrupt drop in transmission percentage (from right to left on Graph 1). Comparing the data to the changes present on the graph, it would seem that $\lambda_{cutoff} \approx 1120nm$, as this is the point immediately preceding large changes in the transmission percentage.

Applying equation (6), we can solve for the “unknown” band gap of silicon:

$$E_G (eV) = \frac{1240(eV \cdot nm)}{\lambda_{cutoff} (nm)}$$

$$E_G(eV) = \frac{1240(eV \cdot nm)}{1120nm}$$
$$E_G = 1.107eV$$

Rounding this result to 1.11eV, we find that the experimental value corresponds with the known value of 1.11eV. Assuming two to three significant figures at best, the experimental result is quite accurate

The best possible effort was made to reduce errors; however it is still possible these may have been factors in the final result. Outside sources of light were minimized, but it is possible that external light may have modified the results. Manual control of the monochromator may not have been exact, as well as the readings from the power meter (although they were only taken to three significant figures).

Conclusion:

In this experiment, we successfully determined the band gap of silicon by measuring its optical absorption. Using a silicon wafer, the photon absorption was noted at varying energy levels by measuring a percent transmission versus wavelength. By identifying the wavelength and subsequent energy associated with the transition between majority transmission and absorption, the band gap of the silicon wafer was found to be 1.11eV. This experimental value corresponded accurately within three significant digits of the known value, indicating a successful experiment.