Department of Plasma Physics and Technology

PHYSICAL LABORATORY 3

Physical laboratory 3

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Field: F **Group:** Út 14:00 **Tested:**

Task № **8:** **Band gap width**

1. Tasks

1. Determine the energy band gap of silicon and germanium using the photoelectrict effect.

2. Theory

Solid-state materials can be classified as conductors, semiconductors, or insulators, based on the structure of their electronic energy bands. In semiconductors, the valence band (filled with electrons) and the conduction band (empty at 0 K) are separated by a relatively narrow forbidden band gap E_g. At room temperature, few electrons gain sufficient thermal energy to transition from the valence band to the conduction band, becoming mobile charge carriers. This process also leaves mobile "holes" behind in the valence band.

The width of the band gap E_g is a fundamental property of semiconductors, as it determines the material's electrical and optical behavior. In this experiment, we determine E_g for silicon and germanium based on the *internal photoelectric effect*, which is the generation of electron-hole pairs due to the absorption of photons.

2.1. Internal photoelectric effect

A photon with energy $E \geq E_g$ can excite an electron from the valence band to the conduction band, creating an electron-hole pair. In a *p-n junction*, such excess carriers are separated by the built-in electric field, generating a *photovoltage* U. The generated voltage depends on both the photon energy and the number of absorbed photons.

The photon energy is related to its wavelength by:

$$E = \frac{hc}{\lambda} \tag{1}$$

where $h = 4.1357 \times 10^{-15}\,\mathrm{eV\,s}$ is Planck's constant, $c = 3.00 \times 10^{8}\,\mathrm{m/s}$ is the speed of light, λ is the wavelength in meters. In electronvolts, this becomes:

$$E[\mathrm{eV}] = \frac{1240}{\lambda[\mathrm{nm}]} \tag{2}$$

2.2. Photovoltage normalization

Since the incident light intensity is not constant over all wavelengths, we normalize the measured photovoltage $U(\lambda)$ by the relative photon flux $N(\lambda)$, which is proportional to the spectral intensity $D(\lambda)$ of the halogen lamp:

$$S(\lambda) = \frac{U(\lambda)}{D(\lambda)} \sim \frac{U(\lambda)}{N(\lambda)} \tag{3}$$

This normalized response $S(\lambda)$ reflects the sensitivity of the photodiode at given wavelengths. A non-zero value of $S(\lambda)$ indicates that the photon energy is sufficient to create electron-hole pairs, i.e., $E \geq E_g$.

2.3. Determination of the band gap

To determine the band gap, we follow these steps:

1. Measure the photovoltage $U(\lambda)$ for each wavelength using both silicon and germanium photodiodes.
2. Use the tabulated values of $D(\lambda)$ to calculate $S(\lambda) = \frac{U(\lambda)}{D(\lambda)}$.
3. Convert wavelengths to photon energies using $E = \frac{1240}{\lambda}$.

4. Plot the dependence $S(E)$ and determine the **threshold energy** where S becomes non-zero.

5. This threshold energy is identified as the **band gap width** E_g.

The resulting E_g values for silicon and germanium can then be compared to literature values[1] (approximately $E_{g,\mathrm{Si}} \approx 1.1\,\mathrm{eV}$, $E_{g,\mathrm{Ge}} \approx 0.66\,\mathrm{eV}$) to assess the accuracy of the measurement.

3. Results

For calculating the normalised photovoltage response, it is necessary to extrapolate the data for the lamp's spectral radiation intensity. This is done by fitting a third-order polynomial on the discrete data from the manual's appendix. We get a relation illustrated on Fig. 1:

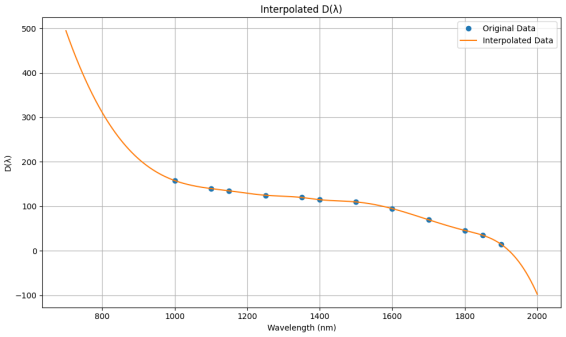

Figure 1: Halogen lamp spectral radiation intensity

As we have acquired $D(\lambda)$ in the appropriate range, we can now use formula (3) to calculate the normalised response for both silicon and germanium. To get $S(\lambda)$ for both semiconductors, we again interpolate the measured data by a third-degree polynomial [1]. The band gap E_g is acquired by finding roots of these polynomials. We get data presented in Fig. 2.

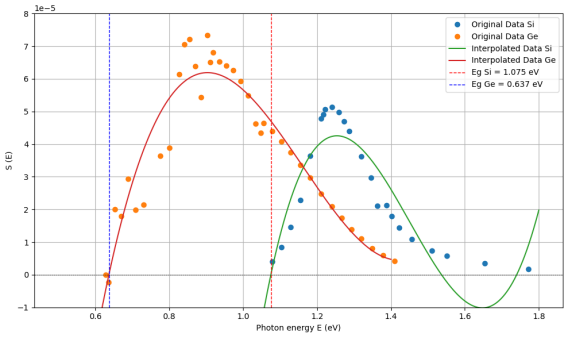

Figure 2: Normalised photovoltage as a function of the light's energy.

To estimate the uncertainty of the extracted band gap energy E_g, we evaluated the standard deviation of residuals between the measured $S(E)$ values and the fitted polynomial:

$$\sigma_S = \sqrt{\frac{1}{N}\sum_i \left[S_i - S_{\mathrm{fit}}(E_i)\right]^2}$$

The uncertainty of E_g was then propagated using the slope of the fitted polynomial at the intersection point:

$$\Delta E_g = \frac{\sigma_S}{\left|\frac{dS}{dE}(E_g)\right|}$$

The band gap values are:

$$E_{g_{\mathrm{Ge}}} = 0.64 \pm 0.19\,\mathrm{eV} = 1.0 \pm 0.3 \cdot 10^{-19}\,\mathrm{J}$$
$$E_{g_{\mathrm{Si}}} = 1.075 \pm 0.15\,\mathrm{eV} = 1.7 \pm 0.2 \cdot 10^{-19}\,\mathrm{J}$$

4. Conclusion

Even though our measured data was affected by significant noise (especially measurements for Ge for energies lower than 1.0 eV) which we are not able to explain, we have successfully acquired the band gap values for both silicon and germanium. By comparing our results to literature [1], we can see that our results are within satisfactory deviation from the real values. This deviation can be explained by our voltage measurement and monochromator resolution, the interpolation of the halogen lamp's spectral intensity distribution - we cannot be sure that the distribution is constant over the lamp's lifespan. The experiment is also dependent on temperature.

[1] Even though the third degree polynomial does not exactly copy the whole curve, it is a sufficient approximation. Higher degree polynomials would not change the result significantly

5. Appendix - measured data

λ [nm]	U [mV]	D(λ)	S(λ) $\cdot 10^6$	E [eV]
880.000	0.930	222.529	4.179	1.410
900.000	1.230	206.903	5.945	1.379
920.000	1.560	193.484	8.063	1.349
940.000	2.010	182.079	11.039	1.320
960.000	2.400	172.493	13.914	1.292
980.000	2.850	164.531	17.322	1.266
1000.000	3.300	158.000	20.886	1.241
1025.000	3.750	151.551	24.744	1.210
1050.000	4.350	146.655	29.661	1.182
1075.000	4.800	142.931	33.583	1.154
1100.000	5.250	140.000	37.500	1.128
1125.000	5.610	137.483	40.805	1.103
1150.000	5.940	135.000	44.000	1.079
1175.000	6.150	132.284	46.491	1.056
1185.000	5.700	131.167	43.456	1.047
1200.000	6.000	129.517	46.326	1.034
1225.000	6.960	126.991	54.807	1.013
1250.000	7.410	125.000	59.280	0.993
1275.000	7.740	123.709	62.566	0.973
1300.000	7.860	122.766	64.024	0.954
1325.000	7.950	121.689	65.330	0.936
1350.000	8.160	120.000	68.000	0.919
1362.500	7.740	118.808	65.147	0.911
1375.000	8.610	117.484	73.286	0.902
1400.000	6.240	115.000	54.261	0.886
1425.000	7.230	113.394	63.760	0.871
1450.000	8.100	112.393	72.069	0.856
1475.000	7.860	111.446	70.528	0.841
1500.000	6.750	110.000	61.364	0.827
1550.000	4.050	104.256	38.847	0.800
1600.000	3.450	95.000	36.316	0.775
1700.000	1.500	70.000	21.429	0.730
1750.000	1.140	57.292	19.898	0.709
1800.000	1.350	46.000	29.348	0.689
1850.000	0.630	35.000	18.000	0.671
1900.000	0.300	15.000	20.000	0.653
1950.000	0.060	-25.334	-2.368	0.636
1975.000	0.000	-56.669	-0.000	0.628

Table 1: Data for Ge

λ [nm]	U [mV]	D(λ)	S(λ) $\cdot 10^6$	E [eV]
700	0.900	494.550	1.820	1.772
750	1.350	391.319	3.450	1.654
800	1.800	310.992	5.788	1.551
821	2.100	283.353	7.411	1.511
852	2.700	248.483	10.866	1.456
872	3.300	229.441	14.383	1.423
885	3.900	218.405	17.857	1.402
894	4.500	211.350	21.292	1.388
910	4.200	199.930	21.007	1.363
922	5.700	192.256	29.648	1.346
940	6.600	182.079	36.248	1.320
964	7.500	170.777	43.917	1.287
975	7.800	166.380	46.881	1.273
985	8.100	162.772	49.763	1.260
1000	8.100	158.000	51.266	1.241
1015	7.800	153.923	50.675	1.222
1020	7.500	152.705	49.114	1.216
1025	7.260	151.551	47.905	1.210
1050	5.340	146.655	36.412	1.182
1075	3.270	142.931	22.878	1.154
1100	2.040	140.000	14.571	1.128
1125	1.170	137.483	8.510	1.103
1150	0.540	135.000	4.000	1.079

Table 2: Data for Si

References

[1] W. H. Strehlow and E. L. Cook. "Compilation of Energy Band Gaps in Elemental and Binary Compound Semiconductors and Insulators". In: *Journal of Physical and Chemical Reference Data* 2.1 (1973), pp. 163–200. DOI: 10.1063/1.3253115.