Department of Plasma Physics and Technology

PHYSICAL LABORATORY 3

Physical laboratory 3

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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, a small number of 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" in the valence band behind.

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:

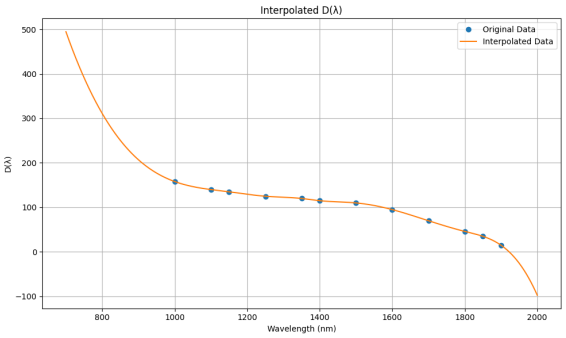

Figure 1: Halogen lamp spectral radiation intensity

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.

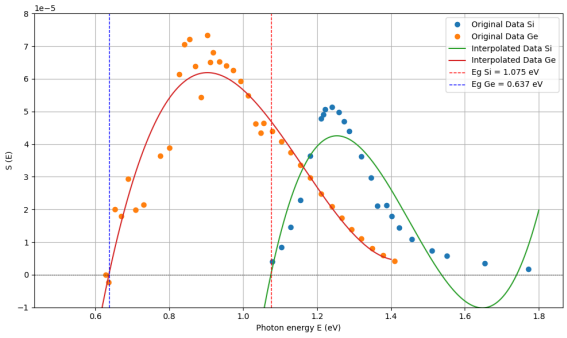

Figure 2: Normalised photovoltage as a function of the light's energy.

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:

$$E_{g\mathrm{Ge}} = 0.64 \pm 0.19\,\mathrm{eV}$$
$$E_{g\mathrm{Si}} = 1.087 \pm 0.15\,\mathrm{eV}$$

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.

[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

Germanium		Silicon	
λ [nm]	U [mV]	λ [nm]	U [mV]
880	0.930	700	0.900
900	1.230	750	1.350
920	1.560	800	1.800
940	2.010	821	2.100
960	2.400	852	2.700
980	2.850	872	3.300
1000	3.300	885	3.900
1025	3.750	894	4.500
1050	4.350	910	4.200
1075	4.800	922	5.700
1100	5.250	940	6.600
1125	5.610	964	7.500
1150	5.940	975	7.800
1175	6.150	985	8.100
1185	5.700	1000	8.100
1200	6.000	1015	7.800
1225	6.960	1020	7.500
1250	7.410	1025	7.260
1275	7.740	1050	5.340
1300	7.860	1075	3.270
1325	7.950	1100	2.040
1350	8.160	1125	1.170
1362.5	7.740	1150	0.540
1375	8.610		
1400	6.240		
1425	7.230		
1450	8.100		
1475	7.860		
1500	6.750		
1550	4.050		
1600	3.450		
1700	1.500		
1750	1.140		
1800	1.350		
1850	0.630		
1900	0.300		
1950	0.060		
1975	0.000		

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.