Calculate Boltzmann and Planck constant using diode

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Abstract:

The Boltzmann constant (K), is a fundamental physical constant that plays a pivotal role in statistical mechanics and semiconductor physics. This study aims to calculate K by analyzing the current-voltage (I-V) characteristic of a silicon diode. Employing the Shockley diode equation and temperature-dependent measurements, we measure K's value in constant temperature using simple diode and resistor circuit with Arduino board as ammeter and voltmeter, and automate the calculation by programming. Our result show a strong agreement with the standard value of Boltzmann constant, with minor deviations attribute to experimental limitations. Future work may explore the application of this method and using single-board micro-controllers such as Arduino as simple educational physics lab equipment.

Theory:

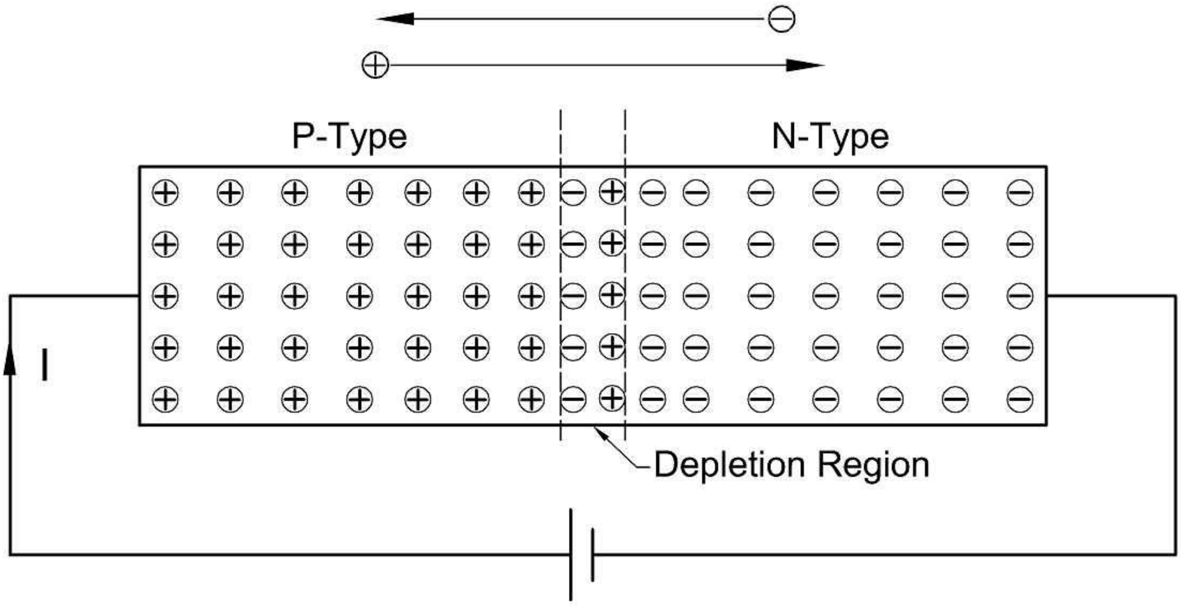
The essential electric characteristic of p-n junction diode is that it constitute a rectifier which permits the easy flow of charge in one direction but retrains the flow in opposite direction. The potential difference across the p-n junction can be applied in two ways, namely; *forward biasing* and *reverse biasing*.

forward biasing: an external voltage applied with the polarity such that negative terminal of the battery is connected to n-side of the junction and the positive terminal to p-side, is called a forward bias. For such a biasing, the height of the potential barrier at the junction will be lowered and the diffusion current due to both electrons and holes, increasing rapidly. The current I is related to the voltage V by the equation.

$$I = I_s [\exp(qV/nkT) - 1]$$

here V is the applied voltage, q is the charge on an electron, k is the Boltzmann's Constant, T is the absolute temperature, n=1 for Ge and 2 for Si and I_S is the reverse saturation current.

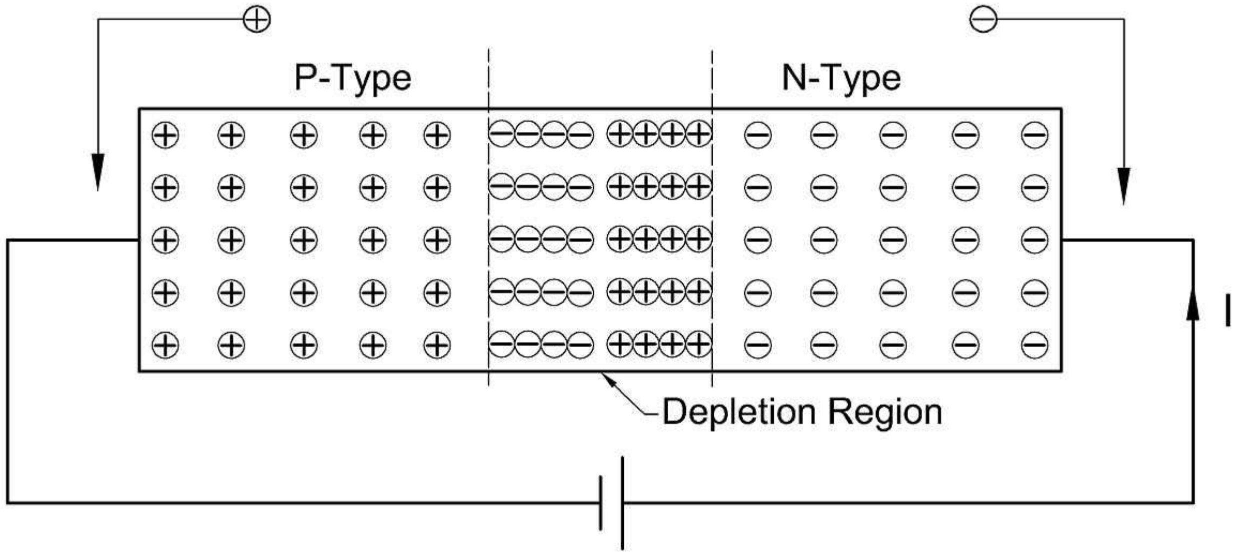
[1] https://github.com/anonzerg/diode



Froward Biased Diode

(*plot I-V characteristic of diode in forward bias*)

reverse biasing: in this type of biasing, the negative terminal of the battery is connected to p-side of the junction, and the positive terminal to the n-side. The polarity of connection is such as to cause both the holes in the p type and the electron in n type to move away from the junction. Consequently, the height of the potential barrier increases. No electrons in the n-side and holes in p-side have enough energy to cross this barrier. Hence the diffusion current is almost negligible for reverse bias. The reverse current is therefore constant, independent of the applied reverse bias. Consequently, I_S is referred to as the reverse saturation current.



Reverse Biased Diode

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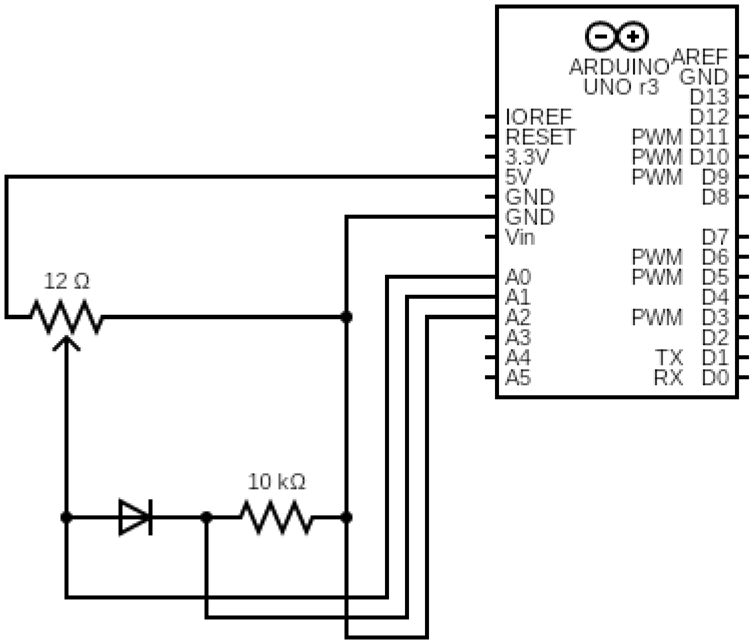
Apparatus:

connect a p-n junction diode, resistor, potentiometer and Arduino Uno 3 board like image below. Connect 3 wire to A0, A1 and A2 to read voltage across diode and resistor. Connect your Arduino to PC and download program from link[1] and follow instruction. Turn potentiometer nob slowly and smoothly from min to max and read values from your monitor. After calculation is done you should be able to see calculated value for Boltzmann constant or Planck constant.



Determine value of Boltzmann's constant:

when a positive potential is applied to the p-side of a p-n junction diode with respect to its n-side, the diode is said to be forward-biased as discussed earlier. If V is the voltage across the junction, the diode current I is given by

$$I = I_s[\exp(qV/nkT) - 1]$$

where I_S is the reverse saturation current,q is the electronic charge, k is the Boltzmann constant, T is the absolute temperature, and n is a numerical constant depending on the material of the diode. For germanium n = 1, and for silicon n = 2.

for silicon diode at room temperature (T = 300 kelvin):

$$I = I_s[\exp(19.3\,V) - 1]$$

where V is the voltage across the diode in volts.

For positive voltage of value 0.5 – 1 volt, the exponential term varies from 1.55*10^4 to 2.41*10^8. hence in this voltage range or above it, we can easily neglect 1 in equation as compared to the exponential term and can write,

[1] https://github.com/anonzerg/diode

$$I = I_s \exp(qV/nkT)$$

$$\log(I) = \log(I_s) + q/2.303n\,kT$$

and finally Boltzmann constant k is calculated from

$$k = \frac{q}{2.303\,nT} \times \frac{1}{slope}$$

.Thus for a silicon diode at 300 K

$$k = \frac{11.59 \times 10^{-23}}{slope}$$

precautions and source of error:

1. ensure the p-side is made positive w.r.t the n-side.
2. increase the supply voltage slowly from zero. Take care that the input voltage does not increase excessively.
3. the temperature T should be noted down in kelvin.
4. it should be remembered that n = 1 for germanium diode and n = 2 for silicon diode.

NOTE: we can determine the reverse saturation current at room temperature as the intercept of current axis.

Planck Constant:

When a large enough potential difference is applied across a light-emitting diode (LED), it emits photons that all have the **same wavelength and frequency.** When the LED just begins to glow, the energy, *E*, lost by each electron as it passes through the LED is converted into the energy of a single photon. The energy, *E*, of a photon is equal to:

$$E = hv = \frac{hc}{\lambda}$$

The energy lost by each electron is:

$$E = e\Delta V$$

Equating the two energies gives the equation:

$$e\Delta V = \frac{hc}{\lambda}$$

This equation can then be used to estimate the Planck's constant.

The aim of this experiment is to use the *I–V* characteristics of different colored LEDs to determine the value of the Planck constant. Set up the circuit as shown in the diagram above. The applied voltage can be changed by using the potentiometer. Slowly increase the voltage in steps from 0 V to 5 V until the LED just begins to emit light Note down the threshold voltage the minimum across the LED that is required before any current is able to flow Repeat the procedure for each colored LED.

Plot a graph of ΔV against $1/\lambda$ for the different LEDs and draw a line of best fit This should produce a straight line with slope *hc / e. Measure the gradient and multiply it by e / c to determine Planck's constant:*

$$h = slope \times \frac{e}{c}$$

[1] https://github.com/anonzerg/diode