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Temperature Dependence of Wavelength in Low Power Laser Diodes

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Abstract

Using a digital spectrometer, we measured the change in the emitted wavelength of a commercially available laser diode array at different temperatures and found a linear function describing the wavelength's temperature dependence. The experimental wavelength shift was found to be $\Lambda = 0.25 \pm 0.01\ nm \cdot K^{-1}$, which is in agreement with literature values. However, our results can still be refined given how many potential sources of error we couldn't account for. We conclude by noting that there is in fact a linear intensity shift which is consistent with Plank's energy formula.

1 Introduction

The invention of the first working laser is largely attributed to Doctor Theodore Maiman, who developed a laser made of synthetic ruby crystal capable of emitting red light [1]. Ever since then, lasers have seen important use in applications ranging from radar technology to optical fibre communications.

For the purposes of our experiment, we will mainly consider two types of lasers, namely the Fabry-Perot (FP) type and the distributed-feedback (DFB) type. FP lasers are cheaper to produce, but mainly work in multi-longitudinal modes, thus these lasers have a large spectral width [2]. This makes them perfect for low-cost applications that don't need to output very precise wavelengths over long distances. On the other hand, DFB lasers are typically built with an internal Bragg grating, which allows for single-mode behavior and a much narrower spectral width about their center wavelength [3].

Many applications require heavy modulation of the source temperature as it is essential for them to have a stable source transmitter of wavelength and intensity [1]. And indeed, it has been found that an increase in temperature leads to a decrease in emission intensity of the laser power due to an increase in phonon energy, as described by Yulianto et al. [1]. That is, there is a greater amount of mechanical energy in the semiconductor within the diode. This leads to a decreased change in energy when an electron combines with an electron hole, consequently producing a lower frequency photon. Precisely knowing the influence of variable temperatures on the wavelength and intensity of laser diodes is of extreme importance, since different types of lasers will vary differently depending mostly on their internal structure. Previous research indicates that the relationship between temperature T, and wavelength λ, is linearly dependent [4],

$$\lambda = \Lambda T + b, \tag{1}$$

where Λ is the coefficient of the shift and b is the offset. Further, it has been shown that there is a clear decrease in intensity of the output power as the temperature is increased. With that in mind, this paper will aim to find whether that dependence can be ascertained and quantified in commercially available low power laser diode arrays.

2 Materials and Methods

After setting up our apparatus as in Figure 1, we turned on the variac and set the voltage to approximately 70 V, enough to partially power the oven. The oven settings were left on low and we would increase the voltage from the variac to control the temperature. After the temperature had increased, we turned off the variac and let the laser diode that was inside come to thermal equilibrium. After waiting a few minutes, we opened the door and immediately measured its wavelength with the digital spectrometer and measured the diode's temperature by placing a thermometer as close as possible to the diode's opening. To be as precise as possible, we always measured the temperature at the same spot. We repeated these steps multiple times at increasing temperatures. Additionally, we occasionally let the diode completely cool down so that we could verify if the wavelength shift was due to the heat or if it was due to irreversible damage to the diode. Unfortunately, we had to replace our laser diode at some point since it broke but the set up and the steps stayed the same.

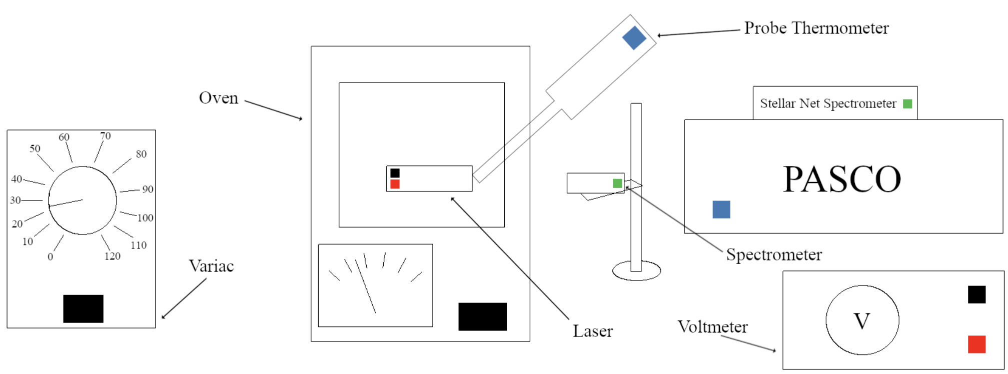

Figure 1: Apparatus used in order to determine the shift in wavelength emission of a diode due to an increase in temperature. Each coloured cube represents a cable connection.

3 Results

Figures 2 and 3 show graphical representations of the wavelength-intensity curve for each temperature. Plotted beneath the curves are the linear fits to the peak wavelengths, which are shown in more detail in Figures 4 and 5. We notice a significant difference in wavelength shift coefficients values (Λ) between the two lasers (see Table 1).

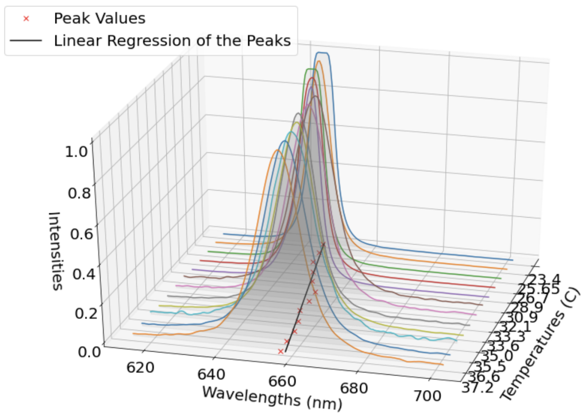

Figure 2: Plot of the wavelengths with a linear regression of the peaks in the z=0 plane to increase the visibility of the shift in wavelength. These measurements we're taken for the first laser. The best fit analysis yields parameters of 0.93 ± 0.02 and $b = 622.4 \pm 0.7$.

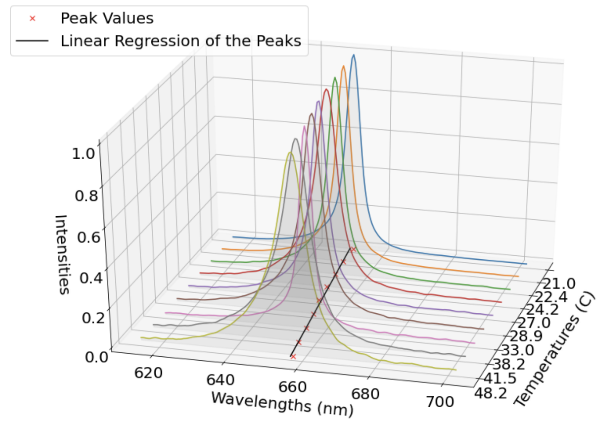

Figure 3: Plot of the wavelengths with a linear regression of the peaks in the z=0 plane to increase the visibility of the shift in wavelength. These measurements we're taken using the second diode. The best fit analysis yields parameters of $a = 0.25 \pm 0.01$ and $b = 645.5 \pm 0.5$.

For each laser diode, the best fit curve was found using a linear regression [5] of the temperatures against their associated wavelengths (Appendix B) and presented in Figures 4 and 5, along with their residual plots. The uncertainties were propagated using the differential method [6].

Comparing our $\Lambda = 0.95 \ nm \cdot K^{-1}$ value from our first laser diode to values found in previous studies [4], we note that it seems to be orders of magnitude greater for unknown reasons. And so, to test the reliability of our data, we tried to measure the spectrum of the first laser at higher temperatures, which ended up with the laser diode ultimately breaking. We acquired a new diode and repeated the experiment, which yielded results that were more in line with expected values of Λ.

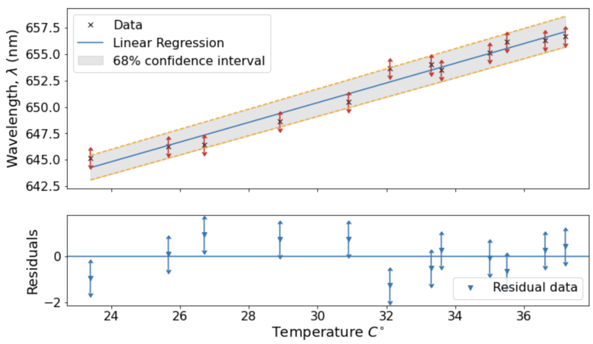

Figure 4: Plot of the data when the temperature was allowed to decrease and testing if the laser would produce the same values after cooling to test for its 'breakage'. The χ^2 test yields $p = 0.268$ showing the data is not significant.

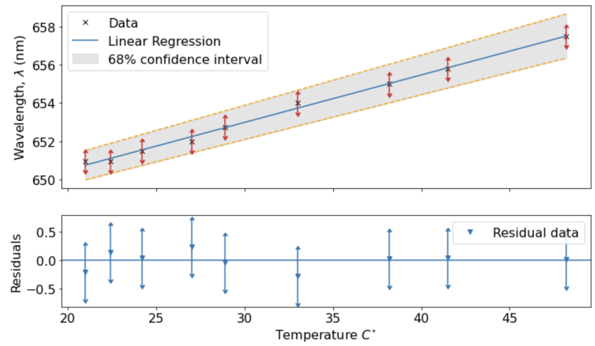

Figure 5: Plot of the linear best fit with residuals when the measurements were taken with the second diode. The χ^2 test yields a p-value of $p > 0.95$.

In more details, following what happened to our first diode, we decided to investigate whether our previous diode's wavelength shift was mainly due to irreversible damage from high operational temperatures, and whether that damage was significant enough to alter our results. To that effect, it was important to observe the spectra of the new laser diode's emissions while it was cooling down. Its graph is depicted in the 3 dimensional plot presented in Figure 6. From the general linear trend in Figure 7, we conclude that the damage we were causing the second laser diode with respect to its expected emission wavelengths seemed to be unsubstantial for the most part, as wavelength readings at neighboring temperatures were in the range of uncertainty.

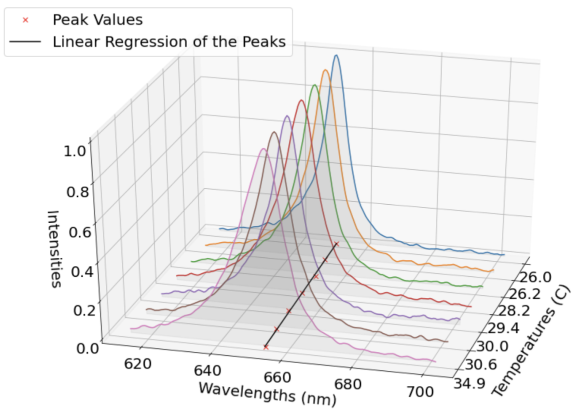

Figure 6: Plot of the data when the temperature of the diode was tested while cooling. This plot allows to test for a 'breakage' point due to damage inflicted to the diode.

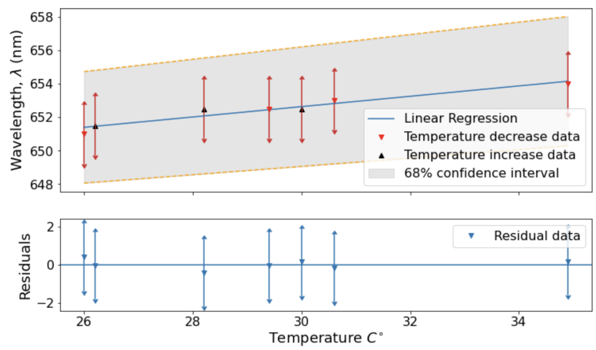

Figure 7: Plot of the linear best fit with residuals when the diode was allowed to cool back down. The red data are points post-heating. It is possible to extract the parameters of the best fit curve such that $a = 0.31 \pm 0.06$ and $b = 643 \pm 1$. The χ^2 test yields a p-value of $p > 0.95$.

Wavelength shift coefficient for each analysis (Λ)

Diode 1	Diode 2	Diode 2 damage test	Literature value
$nm \cdot K^{-1}$			
0.93 ± 0.02	0.25 ± 0.01	0.31 ± 0.06	0.27 ± 0.3 [7]

Table 1: Tabulated values for the Λ coefficient of each run. The uncertainties were extracted from the linear regressions through the differential method [6]. The wavelength shift coefficients were extracted from Figures 4, 5 and 7 respectively. The literature value is taken from J.Bartl's value for the shift in wavelength due to temperature [7] when the temperature increases from 285K to 320K for a commercial red laser diode.

4 Discussion

The numerous sources of error in this experiment make it complicated to perform a proper error propagation through formula 1. This is mostly due to the high uncertainty of the temperature probing of the laser diode. Therefore, we chose to use the associated uncertainties with the linear regression parameters going forward into the data analysis.

As shown in Figures 4 and 5, a clear linear relationship can be established for the temperature dependence of the center wavelength of our diodes. Indeed, the data points closely follow a linear fit with an intercept representing the expected wavelength at 0 Celsius. Looking at the data for our first laser diode with $\Lambda = 0.93 nm \cdot K^{-1}$, it is apparent that our result for this part of the experiment is questionable at best. Though we observe a clear linear trend in the data points collected, the coefficient of wavelength shift obtained is much higher than expected. Coupled with the fact that the χ^2 test we conducted rejects the hypothesis of a linear model for this data set, we choose to neglect the findings found using our first laser diode.

Looking into the reason as to why our first diode broke, we figured that it might be because the diode did not have a heat sink, meaning that excess heat within the circuit couldn't be dissipated, and in turn that the diode was more susceptible to break when subjected to excessively increased temperatures. As mentioned in the results section, this led us to experiment with the breakage point of our second diode (Fig. 6).

From the damage test conducted on the second diode, we noticed that the Λ readings for the second diode while heating up and cooling down were within margins of error from one another. Accordingly, we assume that the second diode did not undergo severe internal damage which lets us safely proceed with the belief that our data for the second diode should follow the expected trend.

Now, as for the working diode, we observe from Table 1 a coefficient of wavelength shift $\Lambda = 0.25 \pm 0.01\ nm \cdot K^{-1}$, which is this time within 1 uncertainty measurement of our literature value $\Lambda = 0.27 \pm 0.3\ nm \cdot K^{-1}$.

On another note, the decreased energy of the emitted photons produced from a laser within a heated environment is an interesting phenomenon since, often, an increase in temperature leads to an increase in energy. However we observed in this experiment a decrease in energy of the emitted photons. Thus, we have verified that by increasing the internal energy within a semiconductor via an increase in temperature, the mechanical energy of the phonons within the material goes up. Thus, when the heated semiconductor is supplied with a current causing an electron hole to combine with an electron, a lower frequency photon is produced, exhibiting decreased energy compared to those emitted at lower temperatures (Appendix C).

Finally, it should be noted that when the external temperature is increased, the energy absorbed by the circuit isn't the only factor that may be affecting the change in wavelength. As heat is increased within the laser, thermal expansion will occur throughout the system.

These are also factors which may have caused the low temperature breakage point of the lasers. The aperture will be slightly deformed, and the diode will get larger. The deformation of the aperture should not change the wavelength significantly, but it may influence the intensity of light emitted, as described by De Esch [8] the intensity of emitted light decreases significantly with an enlarged aperture which occurs in the presence of a higher temperature system.

5 Conclusions

In this paper, the effect of temperature on wavelength was successfully determined. For our second laser, we evaluated the shift accurately and with precision. Unfortunately, we realised that the data for our first laser was inaccurate causing us to believe that it had a defect considering a failed χ^2 test and the lack of accuracy of the measurement. Additionally, we observed a decrease in intensity as the temperature was increased. By finding the different wavelengths at increasing temperatures, we were able to understand that the shift is the product of the increased internal energy of the semiconductor that is emitting the photons and also the thermal expansion of the grating inside the laser. This experiment provides a basis for tuning a laser diode to an exact wavelength, which proves useful in many real world applications. In a future experiment, it would be interesting to measure the effect of temperature on the intensity of the laser and quantifying the thermal expansion that the laser experiences.

Author Contributions Statement

B. Bulgaru, T. Yuhao, T. Jogand-Coulomb and S. Fletcher cooperated taking measurements, coding sample calculations and plots, making figures and tables, writing and reviewing the manuscript.

Acknowledgements

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A Lab Book

1. The laser has Eq. No. EQ3508 with wavelength of 650nm in the -10C to 25C range.

2. The oven is Eq. No. EQ4465

1. Voltage controls the heating element of the oven. The laser is inside the oven. The temperature of the diode is measured using the thermometer and the voltage created from the temperature. The spectra is taken by the spectra wiz.

2. Turn on the variac so that the oven generates some heat, approx. 2 minutes. Turn it off. Let the oven and diode temperatures stabilize for 5 minutes.

3. The thermometer takes a specific reading using the PASCO. The voltmeter takes the 1 mV for every 1^{o}C though there is an offset of roughly 10^{o}C.

4. The thermometer needs roughly 1 minute against the diode to read a correct temperature.

5. The intensity of the emission decreases at higher temperature.

6. At 40C, when changing the DC voltage supplied to the laser, the higher the voltage, the lower the intensity. Is it the internal circuit?

Possible Errors

1. Temperature of the diode may not be consistent throughout.

2. Error introduced by the thermometer.

3. Error and offset introduced by the temperature to mV converter.

4. Error from spectroscopy, scipy.

5. Temperature of diode may change after having taken the spectroscopy measurement since the diode may have cooled as the over was open. Maybe the temperature should be taken first until the thermometer stabilizes, then immediately take the spectral data.

1. Originally, we believed the wavelength of light would increase with higher temperatures. This hypothesis is represented in our data, and we have noticed that it is related linearly with a slope near 1.

B Python program

```
def linear_regression_simple (x_data,y_data):
  """
  (list, list)->(list)
  takes a single data_x, data_y and returns [fit_params,
   uncertainty_params]
  """
  x = n.array(x_data)
  y = n.array(y_data)
  #Calulating the delta
  sum_xi_square = 0
  sum_xi = 0
  sum_yi = 0
  sum_xi_yi = 0
  for i in range (len(x_data)):
    sum_xi_square += x_data[i]**2
    sum_xi += x_data[i]
    sum_yi += y_data[i]
    sum_xi_yi += x_data[i] * y_data[i]
  delta = len(x_data) * sum_xi_square - (sum_xi)**(2)
  #Now we can determine the parameters
  a = (len(x_data) * sum_xi_yi - sum_xi*sum_yi)/delta
  b = (sum_xi_square * sum_yi - sum_xi * sum_xi_yi) /delta

  #Now we can determine the uncertainty on these parameters

  #Lets start by determining the uncertainty on CU
  var_cu = 0
  for i in range (len(x_data)):
    var_cu += (y_data[i]- a * x_data[i]- b)**2
```

```
    var_cu = 1/(len(x_data)-2)

    var_a = var_cu * (len(x_data)/delta)
    var_b = var_cu * (sum_xi_square/delta)

    return [[a, b], [n.sqrt(var_a), n.sqrt(var_b)]]

def linear_regression (measurements):
    """
    (list)->(list)
    Takes a list of measurements [[data_x1, data_y1], [data_x2, data_y2]]
     and returns the fit and uncertianty for the measurements
    st [[fit1, uncertainty_params1], [fit2, uncertainty_paarams2]]
    """
    #We need to convert the file to an array so that we can use math on it
     easily
    measurements = n.array(measurements)
    #Lets start by defining the delta for each fit
    """
    for i in range (len(measurements)):
      if len(list(measurements[i][0])) != len(list(measurements[i][1])):
        print('The data sets need to be of the same size')
        return False
    """
    delta = []
    for i in range (len(measurements)):
      sum_xi_square = 0
      for j in range (len(measurements[i][0])):
        delta += [  len(measurements[i][0]) * ()   ]

def best_fit (x_values, fit):
    """
    (list, list) --> (list)
    function that returns the best fit curve for a polynomial fit
    """
    best_fit_curve = []
```

```
  for i in range (len(x_values)):
    p = 0
    for j in range (len(fit)):
      p += fit[j]*x_values[i]**(len(fit)-1-j)
    best_fit_curve += [p]
  return best_fit_curve

def residuals (best_fit , curve):
  residuals = []
  for i in range (len(best_fit)):
    residuals += [best_fit[i] - curve[i]]
  return n.array(residuals)
```

Source Code 1: Data analysis functions to determine the uncertainties through a linear regression

C Showing the decrease in energy

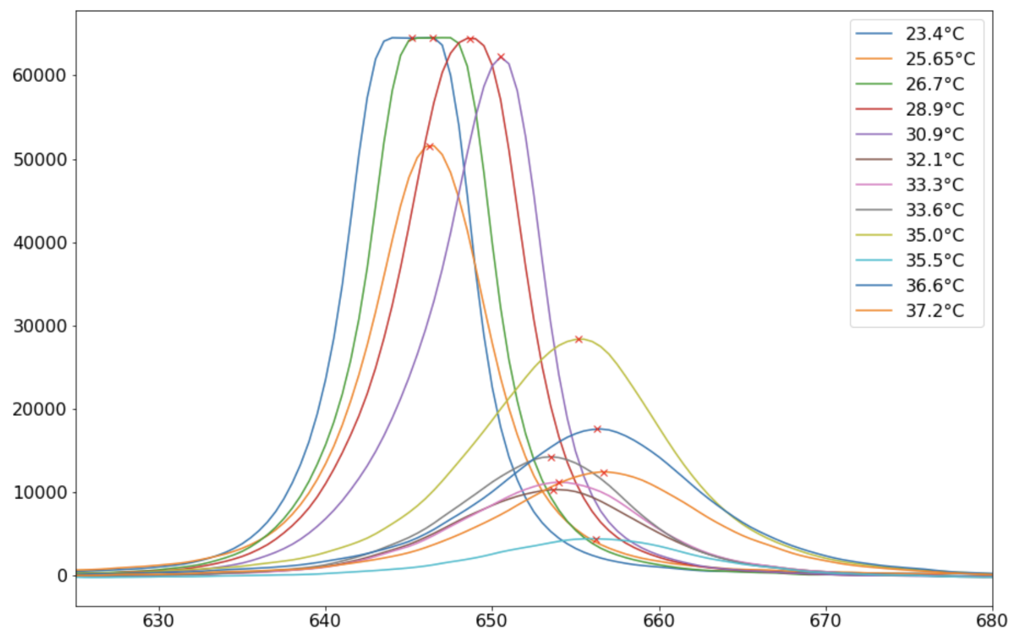

Figure 8: A visualisation of the decrease in intensity due to an increase in temperature. These measurements were taken for the first diode.

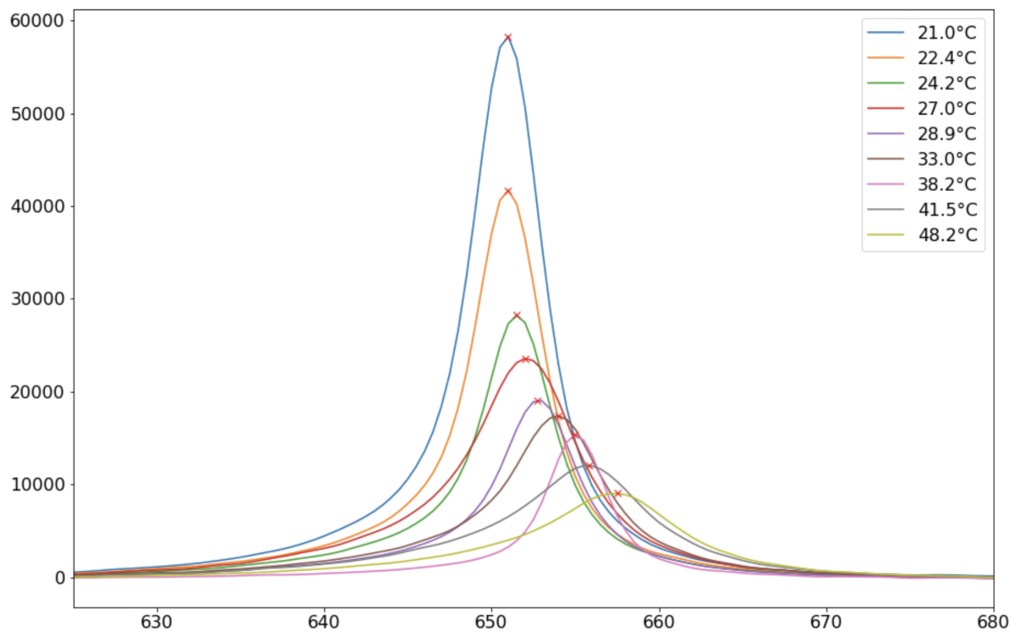

Figure 9: A visualisation of the decrease in intensity due to an increase in temperature. These measurements were taken for the second diode.