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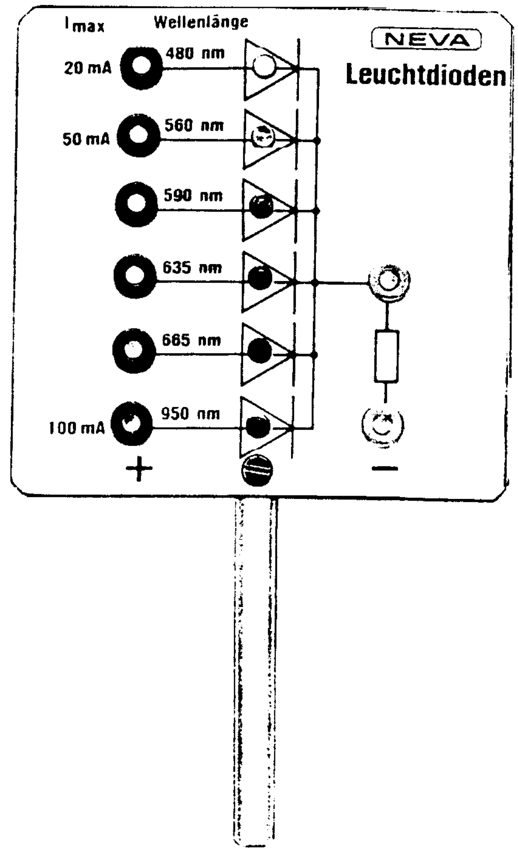

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1. Introduction

Light emitting diodes can be used not only for classical experiments in optics such as wave-length determination, but also for experiments relating to thequantum nature of light. By this simple means, an estimate of the value of Planck's action quantum canbe obtained.

The demonstration of the linear relationship between the photon energy E and the light frequency f is possible with greater accuracy than when using a vacuum photoelectric cell. In addition to the photoelectric effect, X-ray bremsstrahlung and Compton scattering, this experiment constitutes another example of the quantum nature of light.

2. The physics of light emitting diodes

The phenomenon of light generation by electric excitation of a solid body was first observed by H.J.Round (1) in 1907 on silicon carbide (SiC). O.V.Lossew (2), who further investigated this electroluminescent effect during the years 1927 to 1942, already assumed correctly that this is the inverse process with respect to the photoelectric effect discovered by Einstein. A more detailed explanation of the actual mechanism, namely the radiating recombination of minority carriers injected across a pn-junction, was given much later by K. Lehovec in 1951 (3). Independently thereof, in 1935 G. Destriau (4) found a similar luminous effect known by his name, when he applied an electric field to zinc sulfide crystallites. However, the excitation mechanism of this effect differs from that of the injection luminescence found with SiC. The electro- luminescence of ZnS was further developed for technical exploitation in the 1950s.

Whereas no success was achieved here, the III-V compounds recognized to be semiconductors by H.Welker (5) in 1951, brought the desired technical break- through. These semiconductors consisting of one atom each from the third and the fifth column of the periodic system of the elements, have some remarkable properties which distinguish them from the classical semiconductors silicon (Si) and germanium (Ge): First of all, they have a wide spectrum with some band separations E_g much greater than those of Si and Ge, so that their equivalent frequencies $f = E_g/h$ extend into the visible spectral range. Furthermore, some of these semiconductors have much greater efficiency fac- tors for radiating recombination of electrons and holes and in some cases also much greater charge carrier mobilities than Ge and Si. Their complicated technology, which was mastered for technical mass-production not before the end of the 1960s, is the chief reason why these III-V semiconductors are used today only where the above-mentioned advantages over Si and Ge dominate: For luminescent and laser diodes and for highest speed devices.

Luminescent (light emitting) diodes operate according to the principle of injection luminescence, i.e. they are simple pn-diodes, in which with current polarity in the forward direction, some of the charge carriers injected into the neutral n- and p-region recombine radiatively, thereby emitting a photon with energy

$$h \cdot f <= E_g$$

The kind of doping involved here coinsists of so-called isoelectronic lattice defects. In these positions of the crystal lattice, the atom which replaces the normal one comes from the same column of the periodic system of the elements, i.e. in contrast to the case with normal donors and acceptors, these lattice defects make no contribution to the charge carrier balance in the semiconductor. But they differ so greatly from the substituted atom with regard to atomic radius and electronegativity, that charge carriers can be bound. The best known isoelectric lattice defect in Ga(As,P) consists of a nitrogen atom in the place of an arsenic or phosphorus atom. On account of its smaller atomic radius and its greater electronegativity, such a nitrogen atom can bind an electron. By Coulomb interaction, this in turn binds a hole. The bound electron and hole constitute a so-called bound exciton. A photon is emitted when this exciton decays, i.e. when the bound electron and hole recom- bine. The advantage of these isoelectric lattice defects lies in the strong localization of the primarily bound electron. As a result of the Heisenberg uncertainty principle, this leads to a strong increase of the momentum uncer- tainty of the electron and thus to the desired boost of the probability for radiating recombination.

3. Technical data

Limiting data	IR	red	super-red	yellow	green	blue
Inverse bias voltage	4	5	5	5	5	1
Forward current	100	75	50	50	50	25

Characteristic data

Wavelength	950±20	665±15	635±15	590±15	560±15	480±40	nm
Aperture cone	10 deg.	12 deg.	12 deg.	12 deg.	12 deg.	16 deg.	
Composition	GaAs:Si		$GaAs_{0.35}P_{0.65}$:N		GaP:N	SiC	
		$GaAs_{0.6}P_{0.4}$		$GaAs_{0.15}P_{0.85}$:N			

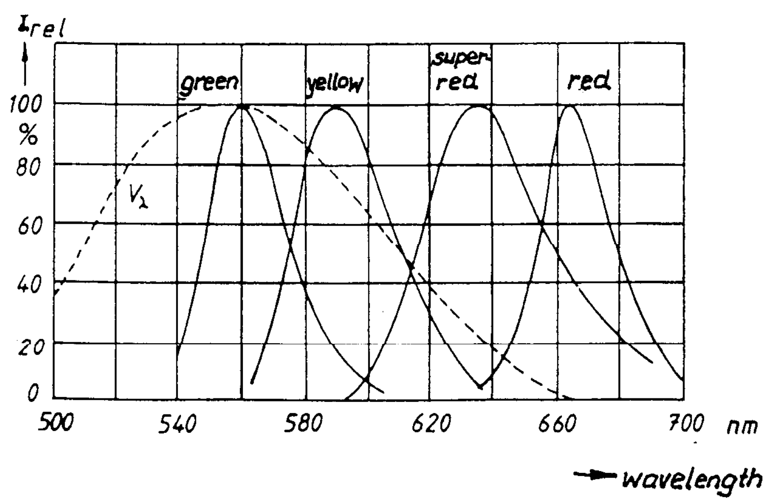

Fig.4 Relative spectral emission curves

Important note:
Connect the power supply voltage to the light emitting diodes only via the built-in series resistor (100 Ohms).

4. Experiments

4.1. Determination of the wavelength with a diffraction at a grating (virtual image of the light emitting diode)

The selected LEDs in the NEVA collection of light emitting diodes are well-suited for subjective observation of diffraction at a grating (No.3942 with 25 lines per mm), by virtue of their predominant radiation in the forward direction and resulting high luminous intensity.

The beam must be restricted by a slit (width < 1 mm), because the coloured plastic body of the chosen diodes radiates light from its entire surface.

Measure the distance delta of the virtual images from the symmetry axis. After setting a known distance D (e.g. 1 m) between the ruler and the diffraction grating, determine by quick change of view through the grating or directly on the ruler, at what distance delta a maximum of highest possible order k appears to lie. The wavelength is then calculated according to the equation

lambda = sin (arctandelta/D) . d/k

where d is the diffraction grating constant.

4.2. Diffraction at a grating in the visible range with real images of the light emitting diode

The light emitting diodes with the colours green, yellow and super-red have sufficient luminous intensity for generating real diffraction images with diffraction gratings in a darkened room. The beam must be restricted with a slit as described in Section 4.1.Fig.5 shows the basic set-up for this experiment. The optical components used here can be taken from the pupil exercise equipments 0013 Optics and 3901 Wave Optics.

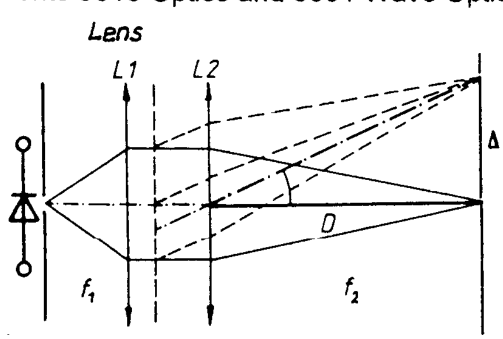

Fig.5 Diagram of ray paths for diffraction with LED at diffaction grating

Evaluate using the equation given in Section 4.1 .

4.3. Diffraction grating with infra-red light

Diffraction of infra-red light at a grating can be demonstrated with the experimental set-up shown in Fig.6 .

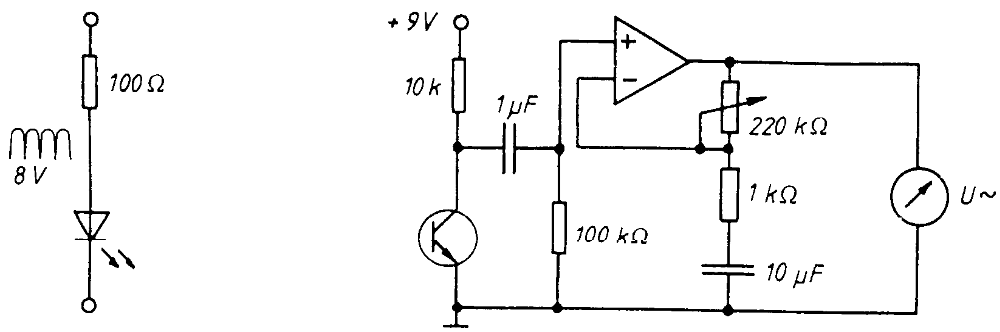

Fig.6 Experimental set-up for diffraction of infra-red light

In this experiment, the light emitting diode is operated with pulsating direct current (8 V from the Universal Transformer 5200). The output voltage of the photo-transistor is further amplified by an operational amplifier and then indicated by an AC voltmeter. Adjust before the actual measurement, using a LED which emits visible light (reduce the power supply voltage to 6 V). The use of alternating light reduces the disturbing effect of ambient illumination, so that only moderate darkening of the room is necessary in order to be able to carry out this experiment.

4.4. The relationship between luminous intensity and current magnitude

As a preliminary experiment before subsequent determination of h, it is useful to observe qualitatively that, on gradually increasing the voltage applied to the diode, emission of lightcommences at the same point at which electric current starts to flow. This observation indicates a causal relationship between these two physical quantities.

4.5. Current/voltage characteristics of light emitting diodes

Fig.7 shows the current/voltage characteristics of all 6 light emitting diodes in one diagram. An XY-chart recorder was used to draw this diagram. The voltage drop across the built-in 100 Ohm resistor was used as measured signal for the vertical axis.

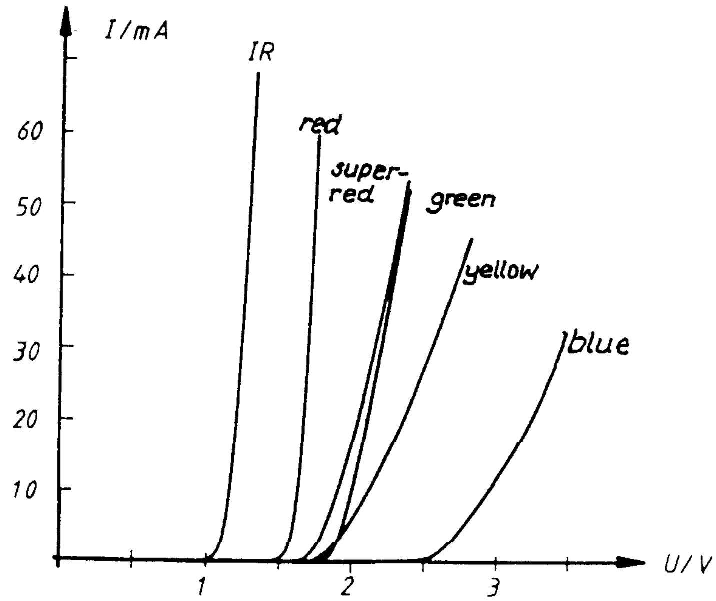

Fig.7U/V

The diffusion voltages U_D are obtained approximately by linear extrapolation of the current/voltage curves to their points of intersection with the voltage axis (U-axis).

4.6. Estimation of Planck's action quantum

Fig.8 shows a plot of the measured values of the diffusion voltages as a function of the frequency f.

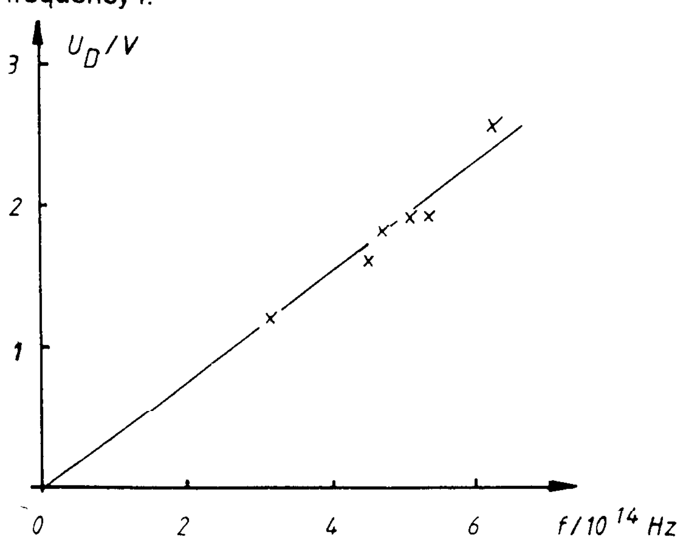

Fig.8 The relationship between the diffusion voltage U_D and the frequency f

The best straight line through the measured points has been drawn on this diagram. According to the explanations given in Section 2, the slope of this line should be

h/e = deltaU_D / delta-f.

The resulting measured value for h/e is

$$3{,}85 \cdot 10^{-15}\ V \cdot s\ (\pm 5\ \%)$$

The error of ± 5 % was estimated from the accuracy with which U_D can be determined.

A comparison with the value 4.1356 . 10^{-15} V . s in standard tables shows that there is a systematic deviation towards values which are too small. The cause for this deviation lies in the use of the relationship

$$e \cdot U_D = h \cdot f$$

Investigations of the dependance of the diffusion voltage U_D on temperature and comparison with technical data books shows that U_D increases as the temperature drops

$1/U_D \cdot (\text{delta}U_D/\text{delta}T) = -\ 5 \ldots 7 \cdot 10^{-4}/K$

This rise can explain the systematic error observed at room temperature.

5. References

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The equality exists in the case of a band to band transition. This is shown in Fig.2 with respect to the energy levels for a pn-junction.

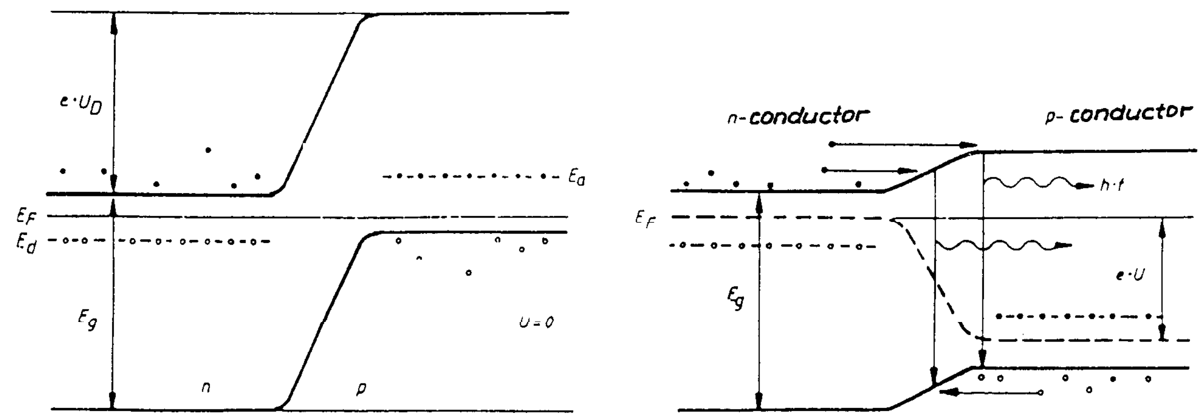

Fig.2 The pn-junction of a light emitting diode

In the absence of an external voltage, a diffusion potential U_D prevails in the barrier layer and prevents electrons from the n-region and holes from the p-region from migrating into the respective other region. A current can flow with significant magnitude only when the external voltage U is greater than (or equal to) the diffusion voltage.

According to Fig.2, the following inequality (conditional equality) is valid for the diffusion voltage U_D

$$e \,.\, U_D <= E_g$$

This relationship follows physically from the requirement that the Fermi energies E_F (chemical potentials) must be the same (in thermodynamic equilibrium) on both sides of the pn-junction when no external voltage is applied. In each case the Fermi energy lies between the donor or acceptor level and the corresponding band edge of the conduction or valency band. The corresponding energy is small compared with the band separation E_g.

The evaluation of the experiment in Section 4 is based on the simple assumption that the energy e . U which the electron has picked-up in the electric field, is emitted entirely as light:

$$e \,.\, U_D = h \,.\, f$$

Thereby U_D is the voltage at which current starts to flow through the diode.