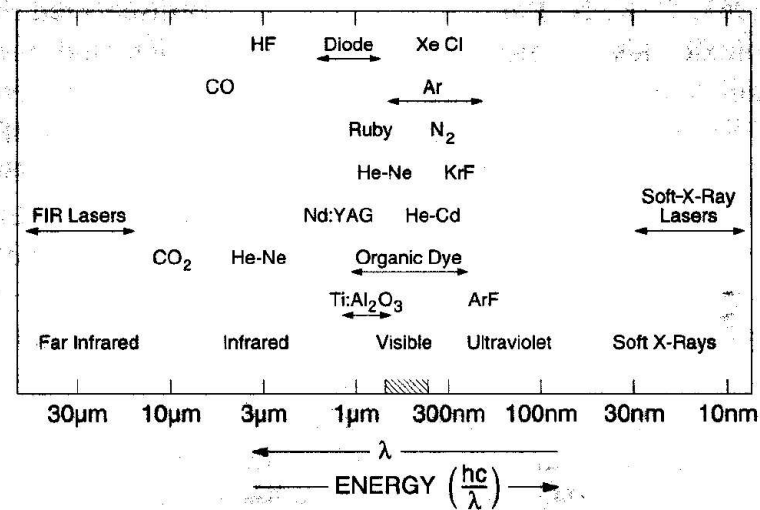
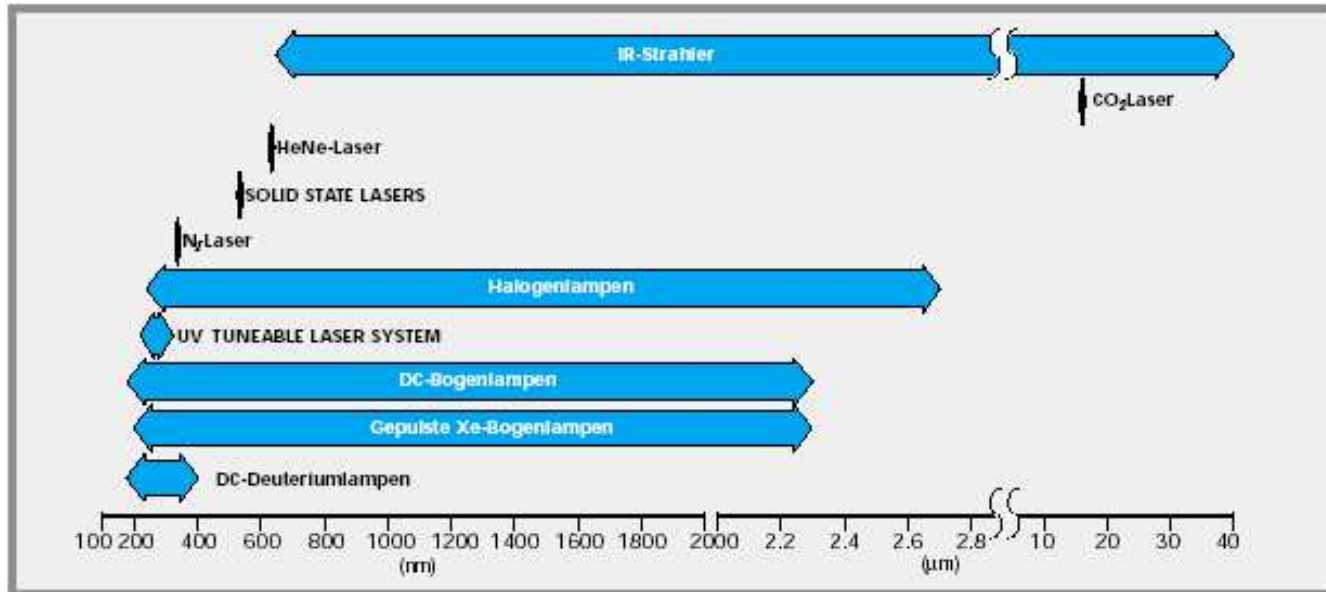


# Licht-/Strahlungsquellen und Detektoren

## *Seminar: Halbleiterspektroskopie*

R. Brüggemann, 08. 05. 03

- Vorbemerkungen
- Licht-/Strahlungsquellen
  - Lampen: Halogenlampe, Bogenlampe
  - LEDs
  - Laser (Gaslaser, Festkörperlaser, Diodenlaser)
- Detektoren
  - Halbleiterdetektoren (Si, Ge, InGaAs, PbS...)
  - Photomultiplier
  - Thermosäule, pyroelektrischer Detektor



Range of laser wavelengths available

## CONVERTING FROM RADIOMETRIC TO PHOTON QUANTITIES

Expressing radiation in photon quantities is important when the results of irradiation are described in terms of cross section, number of molecules excited or for many detector and energy conversion systems, **quantum efficiency**.

### Monochromatic Radiation

Calculating the number of photons in a joule of monochromatic light of wavelength  $\lambda$  is straightforward since the energy in each photon is given by:

$$E = hc/\lambda \text{ joules}$$

Where:

$h$  = Planck's constant ( $6.626 \times 10^{-34}$  J s)

$c$  = Speed of light ( $2.998 \times 10^8$  m s<sup>-1</sup>)

$\lambda$  = Wavelength in m

So the number of photons per joule is:

$$N_{p\lambda} = \lambda \times 5.03 \times 10^{15} \text{ where } \lambda \text{ is in nm}^*$$

Since a watt is a joule per second, one Watt of monochromatic radiation at  $\lambda$  corresponds to  $N_{p\lambda}$  photons per second. The general expression is:

$$\frac{dN_{p\lambda}}{dt} = P_{\lambda} \times \lambda \times 5.03 \times 10^{15} \text{ where } P_{\lambda} \text{ is in watts, } \lambda \text{ is in nm}$$

What is the output of a 2 mW (632.8 nm) HeNe laser in photons per second?

$$2 \text{ mW} = 2 \times 10^{-3} \text{ W}$$

$$\begin{aligned} \phi_p &= 2 \times 10^{-3} \times 632.8 \times 5.03 \times 10^{15} \\ &= 6.37 \times 10^{15} \text{ photons/second} \end{aligned}$$

**Table 3 Spectral Parameter Conversion Factors**

	Wavelength	Wavenumber*	Frequency	Photon Energy**
Symbol (Units)	$\lambda$ (nm)	$\nu$ (cm <sup>-1</sup> )	$\nu$ (Hz)	$E_p$ (eV)
Conversion Factors	$\lambda$	$10^7/\lambda$	$3 \times 10^{17}/\lambda$	$1,240/\lambda$
	$10^7/\nu$	$\nu$	$3 \times 10^{10}\nu$	$1.24 \times 10^{-4}\nu$
	$3 \times 10^{17}/\nu$	$3.33 \times 10^{-11}\nu$	$\nu$	$4.1 \times 10^{-15}\nu$
	$1,240/E_p$	$8,056 \times E_p$	$2.42 \times 10^{14}E_p$	$E_p$
Conversion Examples	200	$5 \times 10^4$	$1.5 \times 10^{15}$	6.20
	500	$2 \times 10^4$	$6 \times 10^{14}$	2.48
	1000	$10^4$	$3 \times 10^{14}$	1.24

When you use this table, remember that applicable wavelength units are nm, wavenumber units are cm<sup>-1</sup>, etc.

\* The S.I. unit is the m<sup>-1</sup>. Most users, primarily individuals working in infrared analysis, adhere to the cm<sup>-1</sup>.

\*\* Photon energy is usually expressed in electron volts to relate to chemical bond strengths. The units are also more convenient than photon energy expressed in joules as the energy of a 500 nm photon is  $3.98 \times 10^{-19}$  J = 2.48 eV

## PLANCK'S LAW

This law gives the spectral distribution of radiant energy inside a blackbody.

$$W_{e\lambda}(\lambda, T) = 8\pi hc\lambda^{-5}(e^{ch/k\lambda T} - 1)^{-1}$$

Where:

- T = Absolute temperature of the blackbody
- h = Planck's constant ( $6.626 \times 10^{-34}$  Js)
- c = Speed of light ( $2.998 \times 10^8$  m s<sup>-1</sup>)
- k = Boltzmann's constant ( $1.381 \times 10^{-23}$  JK<sup>-1</sup>)
- $\lambda$  = Wavelength in m

$$u(\nu) = \frac{8\pi h \nu^3}{c^3} \frac{1}{\exp(h\nu/kT) - 1}$$

$u(\nu)d\nu$  is the energy per unit volume of black body radiation with frequency between  $\nu$  and  $\nu+d\nu$ .

## WIEN DISPLACEMENT LAW

This law relates the wavelength of peak exitance,  $\lambda_m$ , and blackbody temperature, T:

$$\lambda_m T = 2898 \text{ where } T \text{ is in kelvins and } \lambda_m \text{ is in micrometers.}$$

The peak of the spectral distribution curve is at  $9.8 \mu\text{m}$  for a blackbody at room temperature. As the source temperature gets higher, the wavelength of peak exitance moves towards shorter wavelengths. The temperature of the sun's surface is around 5800K. The peak of a 6000 blackbody curve is at  $0.48 \mu\text{m}$ , as shown in Fig. 3.

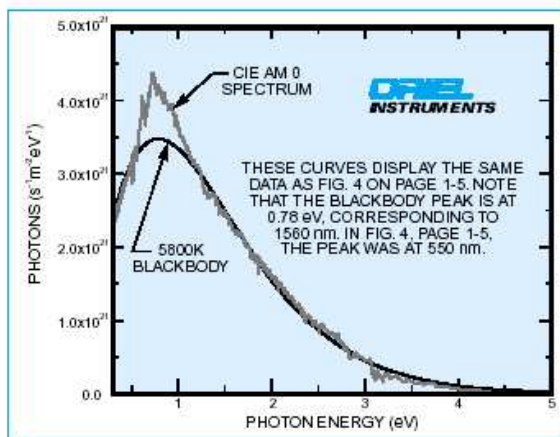


Fig.1 Unconventional display of solar irradiance on the outer atmosphere and the spectral distribution of a 5800K blackbody with the same total radiant flux.

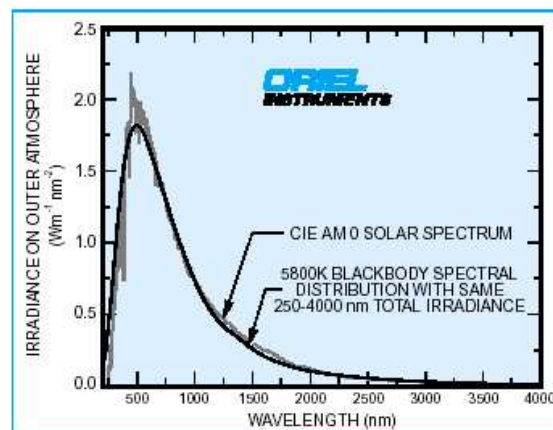


Fig. 1 The spectrum of radiation from the sun is similar to that from a 5800K blackbody.

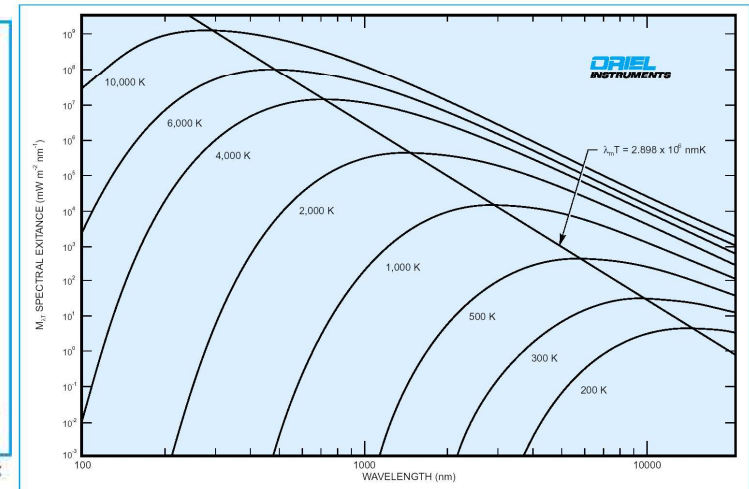
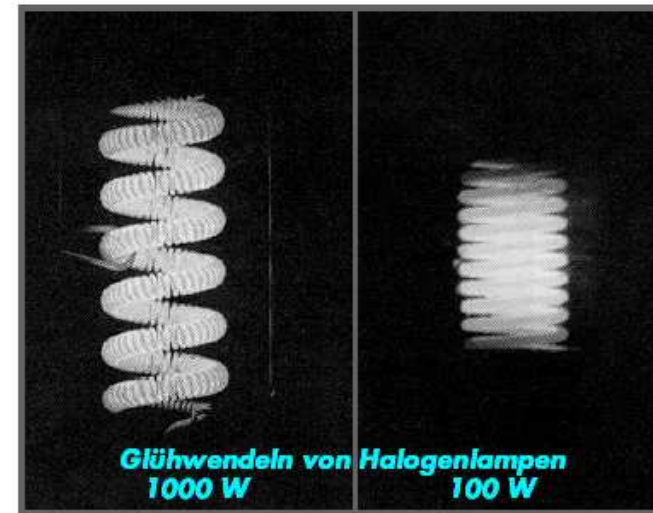


Fig. 3 Spectral exitance for various blackbodies



## Eigenschaften

- hohe Strahldichte im UV und im Sichtbaren. Quecksilberlampen haben Spektrallinien mit sehr hoher Strahldichte im UV.
- hohe UV-Ausgangsleistung
- kleindimensionierter Lichtbogen
- Xenonlampen haben eine spektrale Verteilung, die dem Sonnenlicht sehr ähnlich ist.



## Eigenschaften

- Emission von 350 nm bis 2700 nm
- gute Stabilität
- hohe Ausgangsleistung im Sichtbaren
- gut geeignet als photometrische oder radiometrische Quellen
- Kontinuumstrahler, d.h. relativ geringe spektrale Intensitätsänderung

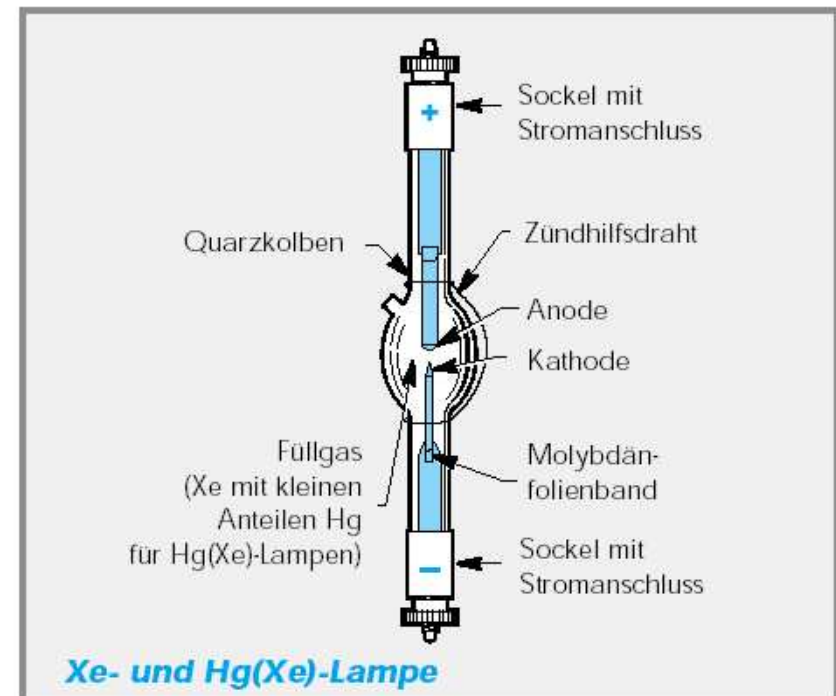
## Xenon-Bogenlampen

Xenon-Bogenlampen sind mit reinem Xe-Gas bei einem Überdruck von 2 – 8 bar gefüllt. Im Betrieb verdreifacht sich der Druck. Beim Betrieb von Xe-Lampen mit Gleichstrom, muss die Anode (großflächige, halbkugelförmige Elektrode, positive Spannung) immer oben liegen.

Das Spektrum dieser Lampen ist eine Kombination thermischer Strahlung des erzeugten Plasmas mit überlagerten Xe-Linien. Im UV und Sichtbaren entspricht die Emission in etwa dem Kontinuum eines schwarzen Körpers von 5500 K (Farbtemperatur). Bei 750 und 1000 nm sind starke Xe-Linien überlagert. Die Ausführungen mit Suprasil-Kolben emittieren bis hinunter zu 170 nm im UV. Ozonfreie Lampen absorbieren unterhalb von 300 nm und emittieren unter 250 nm überhaupt nicht.

## Quecksilber-Bogenlampen

Quecksilber-Bogenlampen enthalten ein Edelgas (Argon oder Xenon) sowie Quecksilber. Die Hitze des Lichtbogens verdampft das Quecksilber. Das Edelgas beschleunigt die Aufwärmung und verbessert die Bogenstabilität und die Lampenlebensdauer. Im kalten Zustand ist der Gasdruck niedriger als der Atmosphärendruck, und Sie können kleine Quecksilberkugeln im Inneren des Kolbens sehen.



Halogenlampen sind Temperaturstrahler. D.h. das Licht wird dadurch erzeugt, dass ein Festkörper auf hohe Temperatur gebracht wird. Je höher seine Temperatur, umso „heller“ leuchtet er. Bei Halogenlampen wird diese Temperatur mittels Stromdurchgang durch einen Leiter erzeugt. Dieser Leiter muss einen hohen Schmelzpunkt und eine niedrige Verdampfungsrate haben. Heute werden alle elektrischen Glühlampen mit Wolframdrähten und -wendeln hergestellt. Bislang gibt es kein besseres Glühmaterial.

### Der Halogen-Kreisprozess

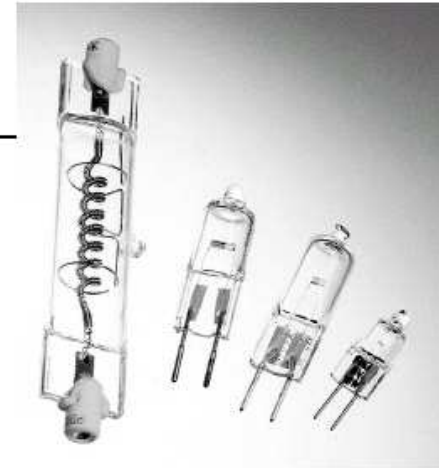
Ein wesentlicher Nachteil klassischer Glühlampen (ohne Halogen) ist die Lichtstromabnahme während der Lebensdauer. Das verdampfende Wolfram schlägt sich auf der Kolbenwand nieder. Dieser schwarze Belag absorbiert das erzeugte Licht.

Der Halogen-Kreisprozess (seit 30 Jahren angewendet) schafft hier Abhilfe.

Dem Füllgas (meistens Krypton oder Xenon) sind geringe Mengen eines Halogens (meist Jod- oder Bromverbindungen) zugesetzt.

Beim Betrieb der Lampe spielt sich dann folgender Kreisprozess ab:

Die von dem heißen Leuchtdraht (3300 °C) verdampfenden Wolfram-Atome kühlen in einigem Abstand auf unter 1400 °C ab. Hier verbinden sie sich mit den Halogen-Atomen. Diese Verbindung bleibt bis 250 °C gasförmig. Sind die Lampenkolben klein, so dass deren Innenwand diese Temperatur rasch an allen Stellen überschreitet, schlägt sich die Wolfram-Halogenverbindung nicht darauf nieder. Sie gelangt mit der thermischen Strömung des Füllgases in die Nähe der heißen Wendel, wo sie wieder in ihre Bestandteile Wolfram und Halogen zerfällt. Das Halogen steht dem Kreisprozess erneut zur Verfügung, das Wolfram lagert sich wieder auf der Wendel ab. Resultat: der Glaskolben bleibt sauber.



### Aufbau von Halogenlampen

Die Lampenkolben bestehen (in der Regel) aus Quarzglas. Mit ihm können Kolbentemperaturen bis 900 °C und Betriebsdrücke bis 20 bar zugelassen werden. Man unterscheidet zwischen einseitig und zweiseitig gesockelten Lampen. Die Abb. auf S. 31 zeigen den typischen Aufbau.

Bei den meisten einseitig gesockelten Lampen wird die Zylinderform durch die Quetschung (Stromdurchführung) im unteren Teil und den Pumpstengel-Abzug im oberen Teil unterschiedlich stark verformt.

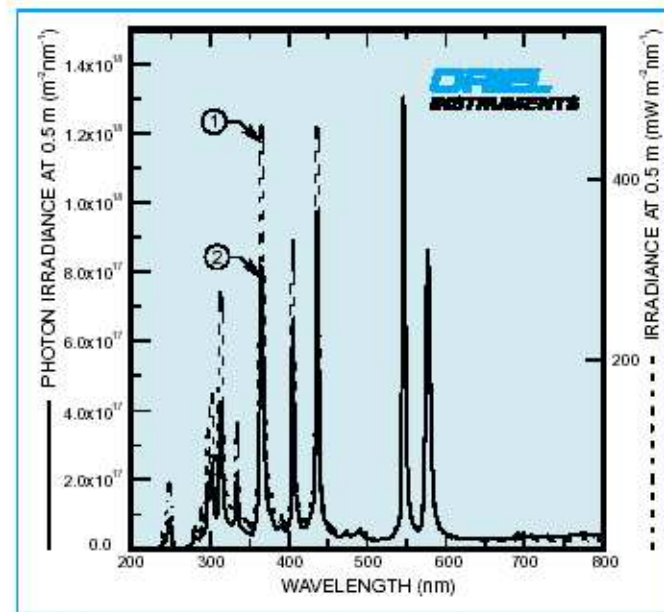
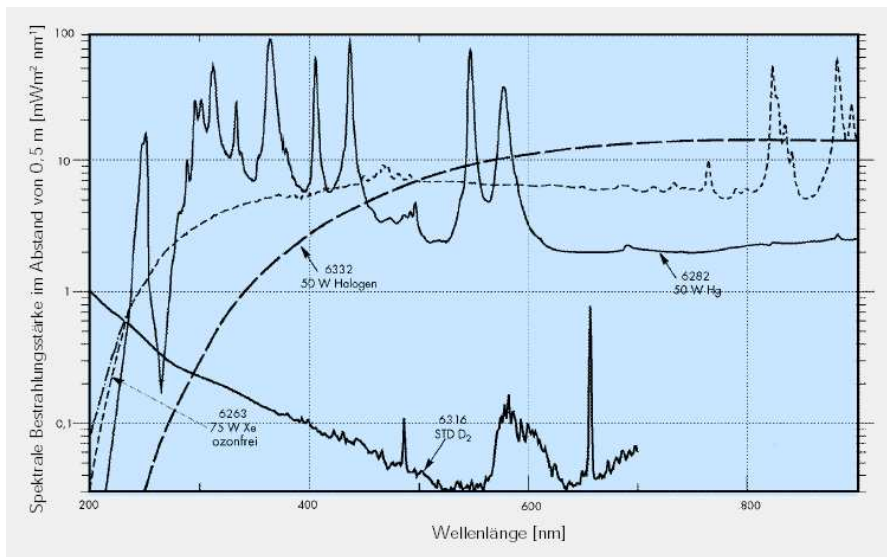
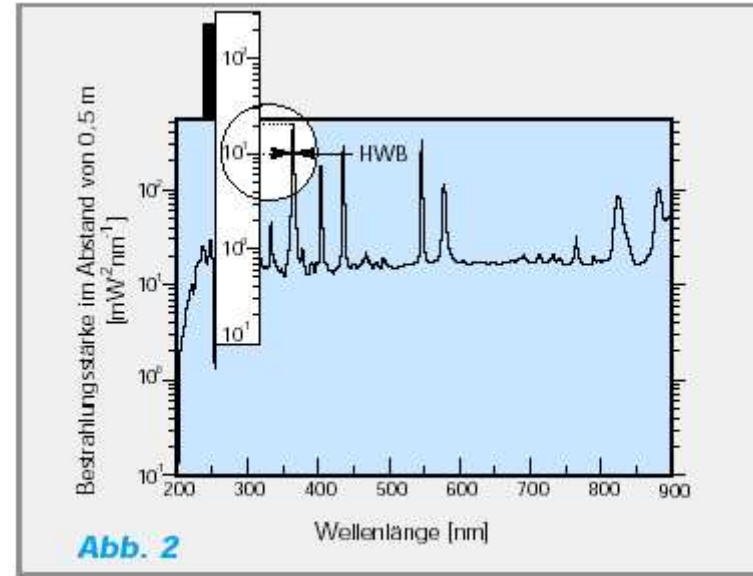
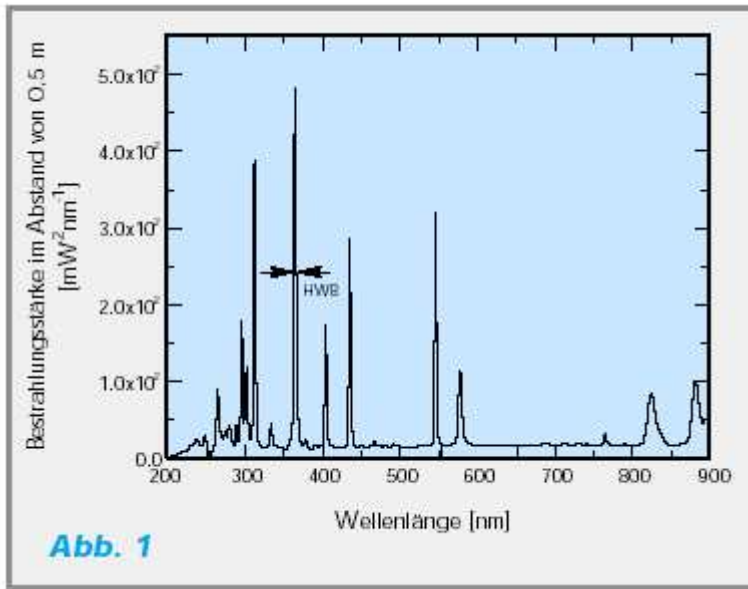


Fig. 2 The wavelength dependence of the irradiance produced by the 6283 200 W mercury lamp at 0.5 m. (1) shown conventionally in  $\text{mW m}^{-2} \text{nm}^{-1}$  and (2) as photon flux.



## Warum eine Deuterium-Lichtquelle?

Deuteriumlampen sind die bevorzugten Strahlungsquellen für die UV-Spektroskopie. Streulicht bereitet in der UV-Spektroskopie große Probleme. Die meisten Strahlungsquellen haben Emissionsspektren wie schwarze Strahler, d.h. geringe Intensität im UV und hohe Intensität im Sichtbaren.

Die meisten Detektoren haben eine höhere Empfindlichkeit im Sichtbaren. Dies führt sehr oft dazu, dass ein durch Streulicht verursachtes Signal im Sichtbaren das eigentliche UV-Signal überstrahlt. Die glatte, kontinuierliche Spektralverteilung von 180 – 370 nm und die geringe Intensität im Sichtbaren und IR einer D<sub>2</sub>-Lampe gewährleisten ein sehr gutes Signal/Rausch-Verhältnis für UV-Messungen.

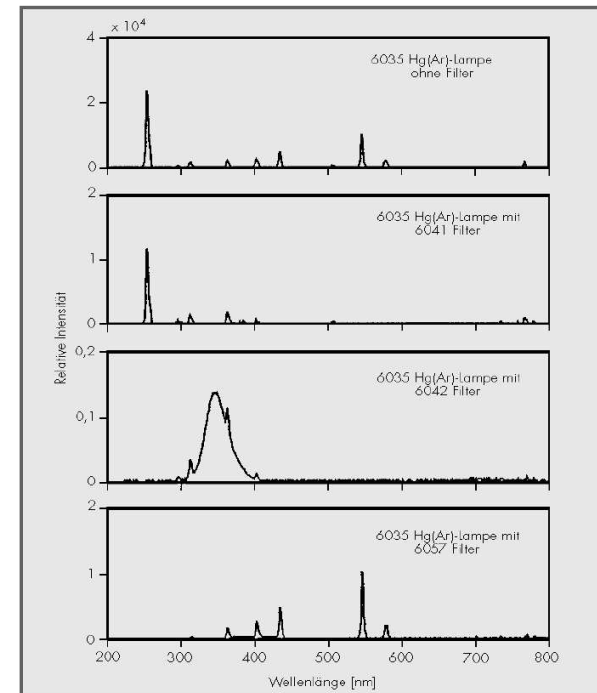
- kontinuierliches UV-Spektrum von 180 – 370 nm
- hohe UV-Intensität mit geringem VIS- und IR-Anteil, daher ideal für UV-Spektroskopie
- einfaches System, sicher zu betreiben
- ozonfreie Versionen

Deuteriumlampen sind Bogenlampen, die mit Deuterium unter niedrigem Druck (einige Torr) gefüllt sind. Die molekulare Deuteriumentladung ist sehr stabil und emittiert ein intensives UV-Kontinuum. Die Emission im Sichtbaren und im IR ist relativ gering. Das Emissionsspektrum ist kontinuierlich von 180 – 370 nm und hat geringe Strukturen ab 400 nm. Die typische Spektralverteilung im Vergleich zu einer Halogen- und einer Xenonlampe ist auf S. 39 zu sehen.

## Spektrale Kalibrierlampen

- diskrete bekannte Spektrallinien
- exzellente Stabilität
- kompakt und einfach zu handhaben

Die genaueste und sparsamste Methode der Wellenlängenkalibrierung ist die spektrale Kalibrierlampe. Unsere spektralen Kalibrierlampen sind stabile Niederdruckentladungslampen (ca. 130 Pa) von der Größe eines Kugelschreibers. Die Emission besteht aus schmalen, diskreten Linien durch Anregung verschiedener Edelgase und Metalldämpfe. Da dieser Anregungs- und Emissionsprozeß (in der Theorie) sehr gut verstanden und dokumentiert ist, sind die Emissionswellenlängen sehr gut bekannt. Daher sind diese Lampen ideal zur Wellenlängenkalibrierung von Monochromatoren, Spektrographen und Spektralradiometern.

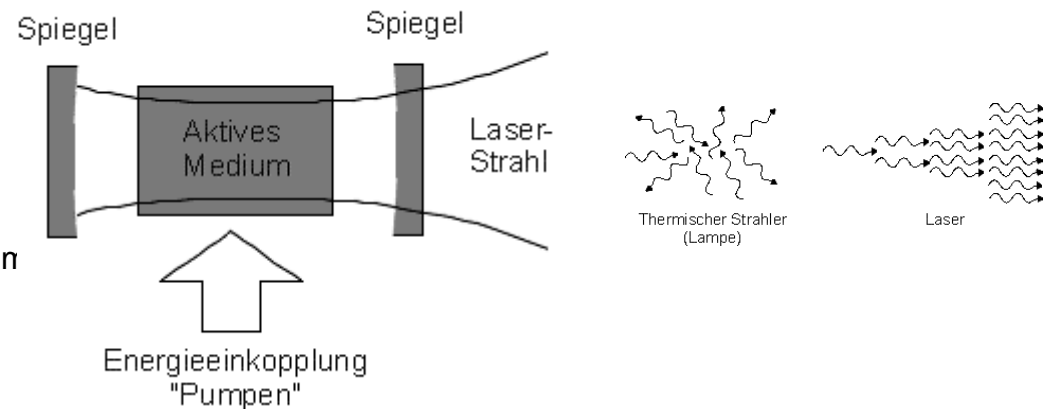


# Laser

- LASER: Acronym für Light Amplification by Stimulated Emission of Radiation - zu deutsch "Lichtverstärkung durch stimulierte Emission von Strahlung".

This is a bit of a misnomer. A laser is actually an *oscillator* rather than a simple amplifier. The difference is that an oscillator has positive feedback in addition to the amplifier. "Light" is understood in a general sense of electromagnetic radiation with wavelength around 1 micron. Thus one can have infrared, visible or ultraviolet lasers.

- Hauptkomponenten:
  - laseraktives, lichtverstärkendes Medium
  - optischer Resonator.
- Erster Laser 1960 von Th. Maiman.
  - Blitzlampen angeregter Rubinlaser
  - Emission im roten Spektralbereich bei 694 nm

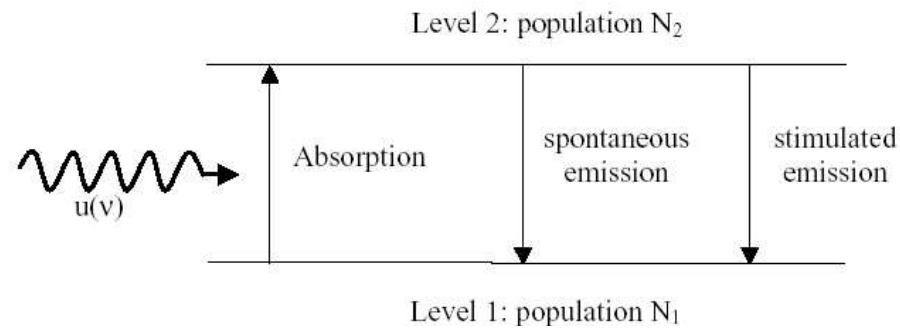


Milestones in the history of lasers:

- 1917 Einstein's treatment of stimulated emission.
- 1951 Development of the maser by C.H. Townes.  
The maser is basically the same idea as the laser, only it works at microwave frequencies.
- 1958 Proposal by C.H. Townes and A.L. Schawlow that the maser concept could be extended to optical frequencies.
- 1960 T.H. Maiman at Hughes Laboratories reports the first laser: the pulsed ruby laser.
- 1961 The first continuous wave laser is reported (the helium neon laser).
- 1964 Nicolay Basov, Charlie Townes and Aleksandr Prokhorov get the Nobel prize for "fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle."
- 1981 Art Schalow and Nicolaas Bloembergen get the Nobel Prize for "their contribution to the development of laser spectroscopy"
- 1997 Steven Chu, Claude Cohen-Tannoudji and William D. Phillips get the Nobel Prize for "development of methods to cool and trap atoms with laser light."

The present state of the art:

Peak powers  $> 10^{12}$  W, pulses shorter than  $10^{-15}$  s, blue laser diodes, ...



Einstein (1917).

atom is inside a box at temperature  $T$  with black walls. bathed in black body radiation.

Spontaneous emission	(2 → 1)	$dN_2/dt = -dN_1/dt = -A_{21} N_2$
Stimulated emission	(2 → 1)	$dN_2/dt = -dN_1/dt = -B_{21} N_2 u(\nu)$
Absorption	(1 → 2)	$dN_1/dt = -dN_2/dt = -B_{12} N_1 u(\nu)$ .

These are effectively the definitions of the Einstein  $A$  and  $B$  coefficients.

$$B_{12} N_1 u(\nu) = A_{21} N_2 + B_{21} N_2 u(\nu) \quad \text{steady state} \quad (2.1)$$

In thermal equilibrium at temperature  $T$ , the ratio of  $N_2$  to  $N_1$  is given by Boltzmann's law:

$$\frac{N_2}{N_1} = \frac{g_2}{g_1} \exp\left(-\frac{h\nu}{kT}\right), \quad (2.2)$$

where  $g_2$  and  $g_1$  are the degeneracies of levels 2 and 1 respectively, and  $h\nu = (E_2 - E_1)$ .

The energy spectrum of a black body source is given by the Planck formula

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{\exp(h\nu/kT) - 1}. \quad (2.3)$$

The only way that equations (2.1) - (2.3) can be consistent with each other at all temperatures is if

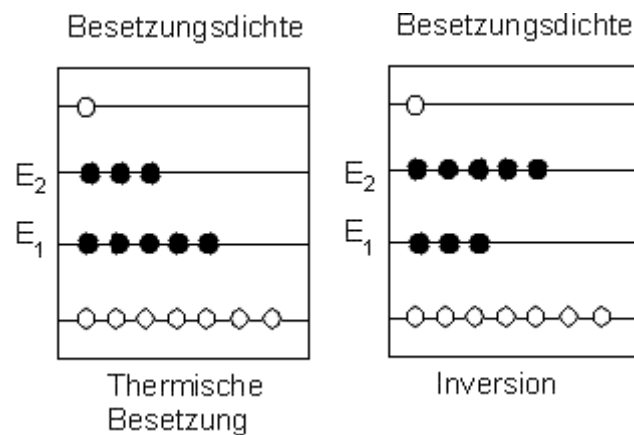
$$\begin{aligned} g_1 B_{12} &= g_2 B_{21} \\ \frac{A_{21}}{B_{21}} &= \frac{8\pi h\nu^3}{c^3}. \end{aligned} \quad (2.4)$$

## Population inversion

In a gas of atoms in thermal equilibrium, the population of the lower level will always be greater than the population of the upper level. (See Eq. 2.2). Therefore, if a light beam is incident on the medium, there will always be more upward transitions due to absorption than downward transitions due to stimulated emission. Hence there will be net absorption, and the intensity of the beam will diminish on progressing through the medium.

To amplify the beam, we require that the rate of stimulated emission transitions exceeds the rate of absorption. This implies that  $N_2$  must exceed  $N_1$ . This is a highly non-equilibrium situation, and is called *population inversion*. Inspection of Eq. 2.2 implies that population inversion corresponds to negative temperatures ! This is not as ridiculous as it sounds, because the atoms are not in thermal equilibrium.

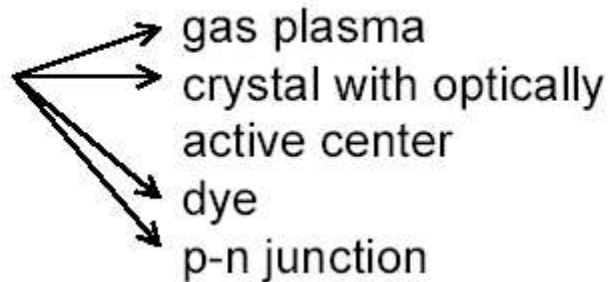
Once we have population inversion, we have a mechanism for generating gain in the laser medium. The art of making a laser operate is to work out how to get population inversion on the transition you want to get lasing.



# Laser

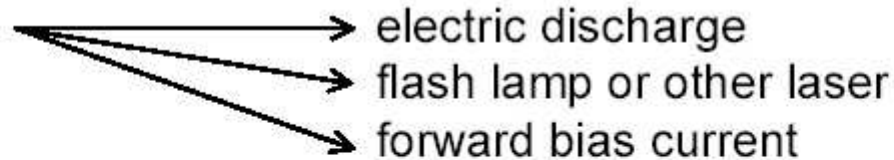
## components:

• optically active medium



gas laser  
solid state laser

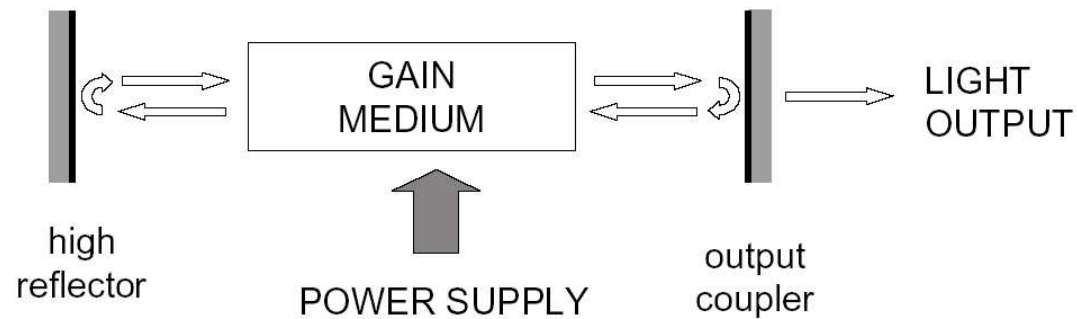
• pump source



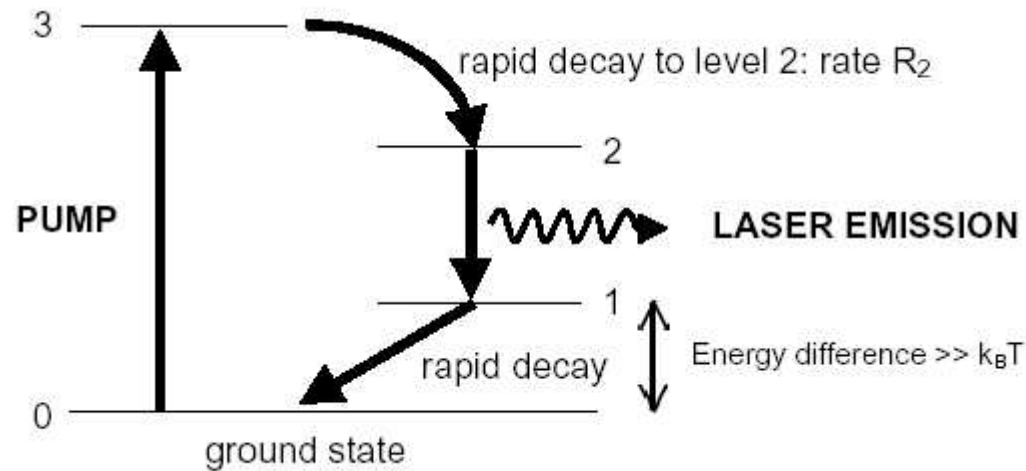
tunable dye laser  
semiconductor laser  
gas-laser  
solid state dye laser  
semiconductor laser

• resonator

planar or confocal mirrors



# Four Level lasers



$$\frac{dN_2}{dt} = -\frac{N_2}{\tau_2} - W_{21}^{net} + R_2$$

$$\frac{dN_1}{dt} = +\frac{N_2}{\tau_2} + W_{21}^{net} - \frac{N_1}{\tau_1}$$

The various terms allow for:

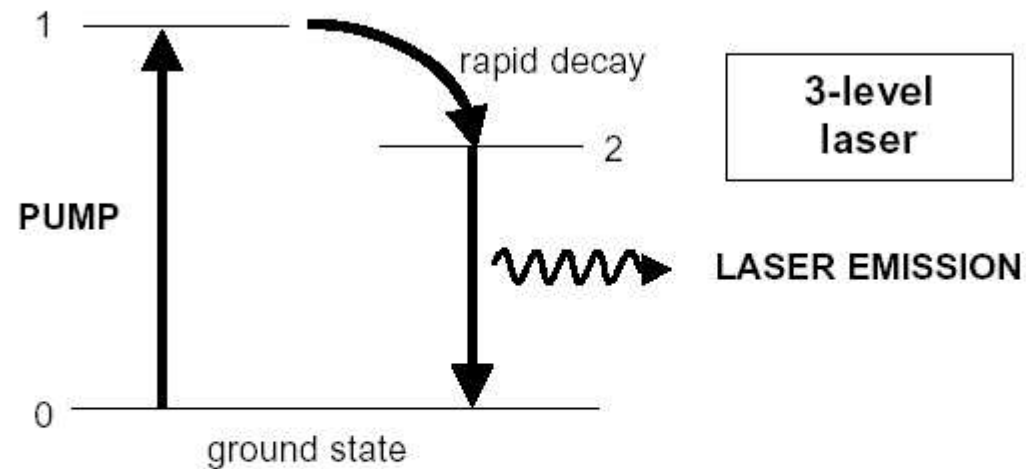
- spontaneous emission from level 2 to level 1 ( $\pm N_2/\tau_2$ ),
- stimulated transitions from level 2 to level 1 ( $\pm W_{21}^{net}$ )
- pumping into level 2 ( $R_2$ ),
- decay from level 1 to the ground state by radiative transitions and/or collisions ( $N_1/\tau_1$ )

Therefore the population inversion is given by

$$\Delta N = N_2 - N_1 = \frac{R_2}{W + 1/\tau_2} \left( 1 - \frac{\tau_1}{\tau_2} \right).$$

This shows that it is not possible to achieve population inversion unless  $\tau_2 > \tau_1$ . This makes sense if you think about it. Unless the lower laser level empties quickly, atoms will pile up in the lower laser level and this will destroy the population inversion.

### 3-Level lasers



Some lasers are classified as being *three-level* systems. The standard example is ruby, which was the first laser ever produced. The key difference between a 3-level laser and a 4-level laser is that the lower laser level is the ground state.

It is much more difficult to obtain population inversion in three level lasers because the lower laser level initially has a very large population.

## Several common types of Gas Lasers

- Neutral atom lasers
  - electronic transitions in atoms: VIS, NIR
  - e.g. He-Ne, Cu vapor
- Ion lasers
  - electronic transitions in ions: UV, VIS
  - e.g. Ar<sup>+</sup>, He-Cd<sup>+</sup>,
- Molecular lasers
  - rotational-vibrational transitions: mid-IR, far-IR
  - CO<sub>2</sub>, CO,
- Excimer lasers
  - electronic transitions in excimer = “excited dimer”: UV  
excited state is bound, ground state not
  - e.g. KrF, ArF, XeF, XeCl
- Chemical lasers
  - exothermic chemical reaction leaves atom/molecule in excited state: IR
  - HF, DF, iodine

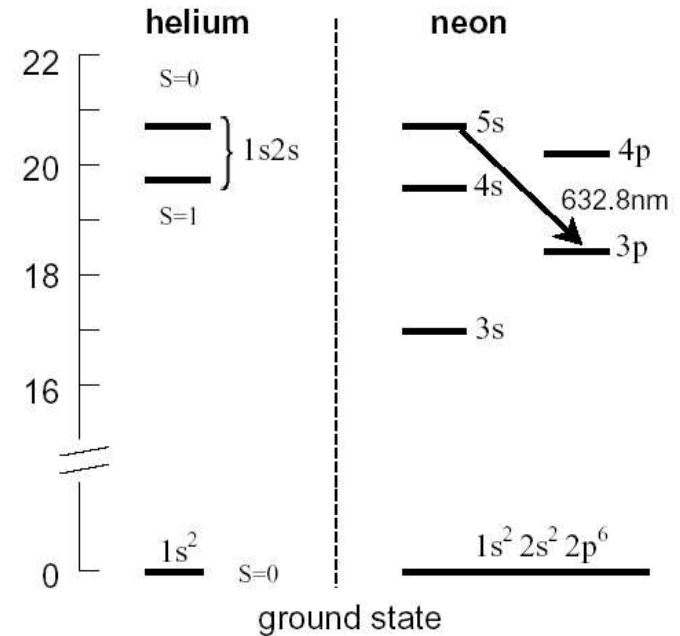
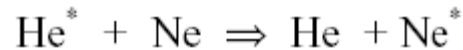
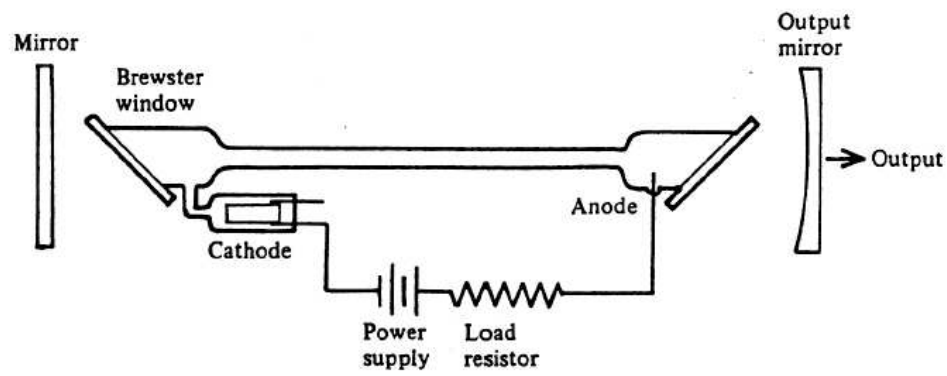
TABLE 10.1. Spectroscopic properties of laser transitions and gas mixture composition in some relevant atomic and ionic gas lasers

Laser Type	He-Ne	Copper Vapor	Argon Ion	He-Cd
Laser wavelength (nm)	633	510.5	514.5	441.6
Cross section ( $10^{-14}$ cm <sup>2</sup> )	30	9	25	9
Upper state lifetime (ns)	150	500	6	700
Lower state lifetime (ns)	10	$\approx 10^4$	$\sim 1$	1
Transition linewidth (GHz)	1.5	2.5	3.5	1
Partial pressures of gas mixture (Torr)	4 (He) 0.8 (Ne)	40 (He) 0.1-1 (Cu)	0.1 (Ar)	10 (He) 0.1 (Cd)

from Svelto



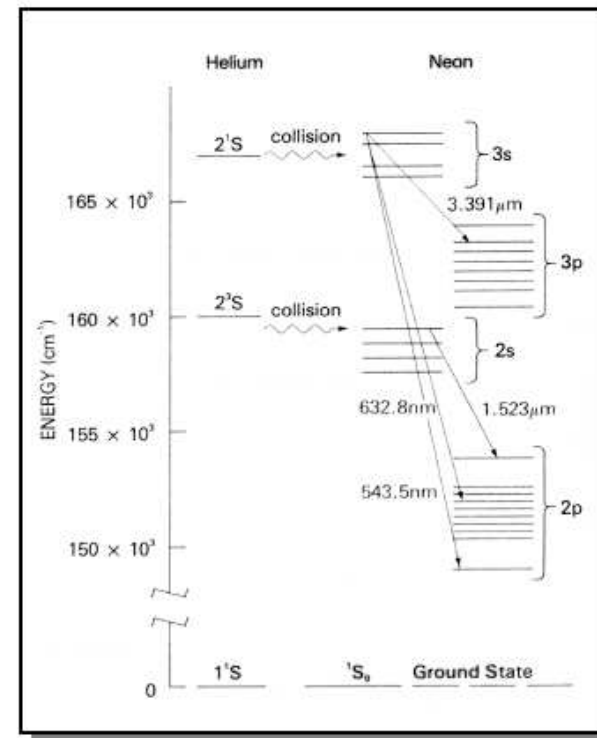
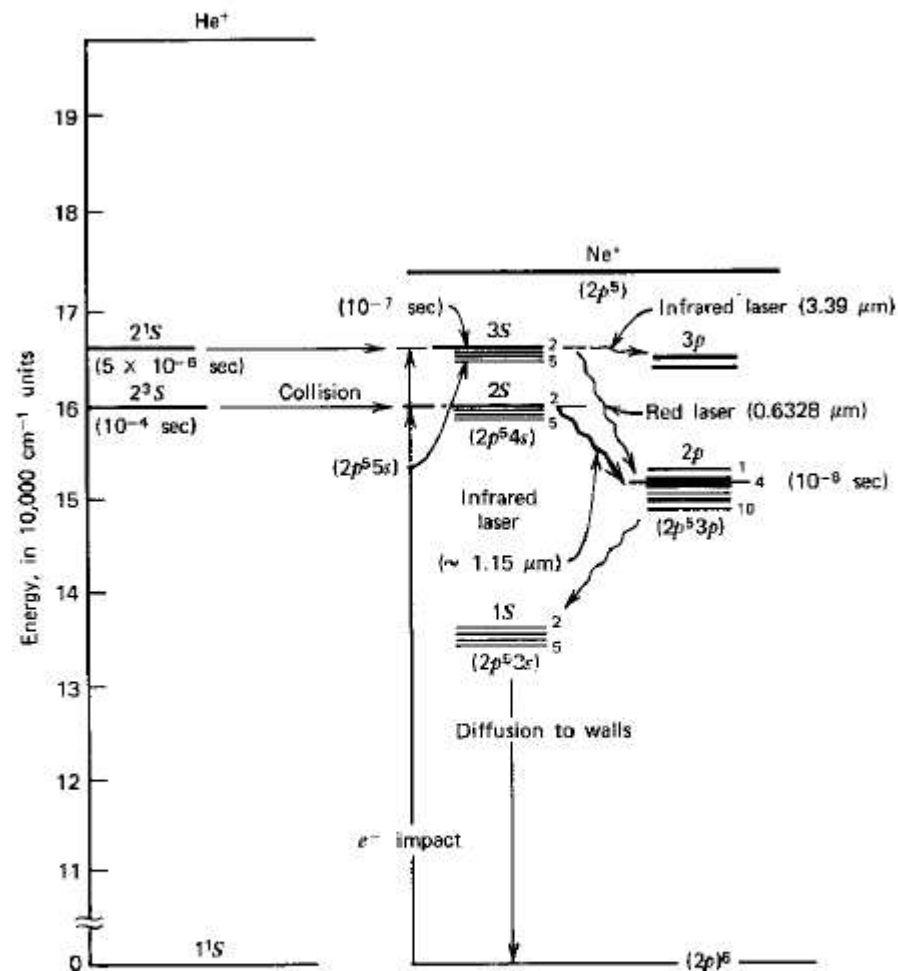
## The Helium Neon (HeNe) Laser



HeNe's consist of a discharge tube inserted between highly reflecting mirrors. The tube contains a mixture of helium and neon atoms in the approximate ratio of He:Ne 5:1. By applying a high voltage across the tube, an electrical discharge can be induced. The electrons collide with the atoms and put them in an excited state. The light is emitted by the neon atoms, and the purpose of the helium is to assist the population inversion process. To see how this works we need to refer to the level diagram

The main laser transition at 632.8 nm occurs between the 5s level and the 3p level.

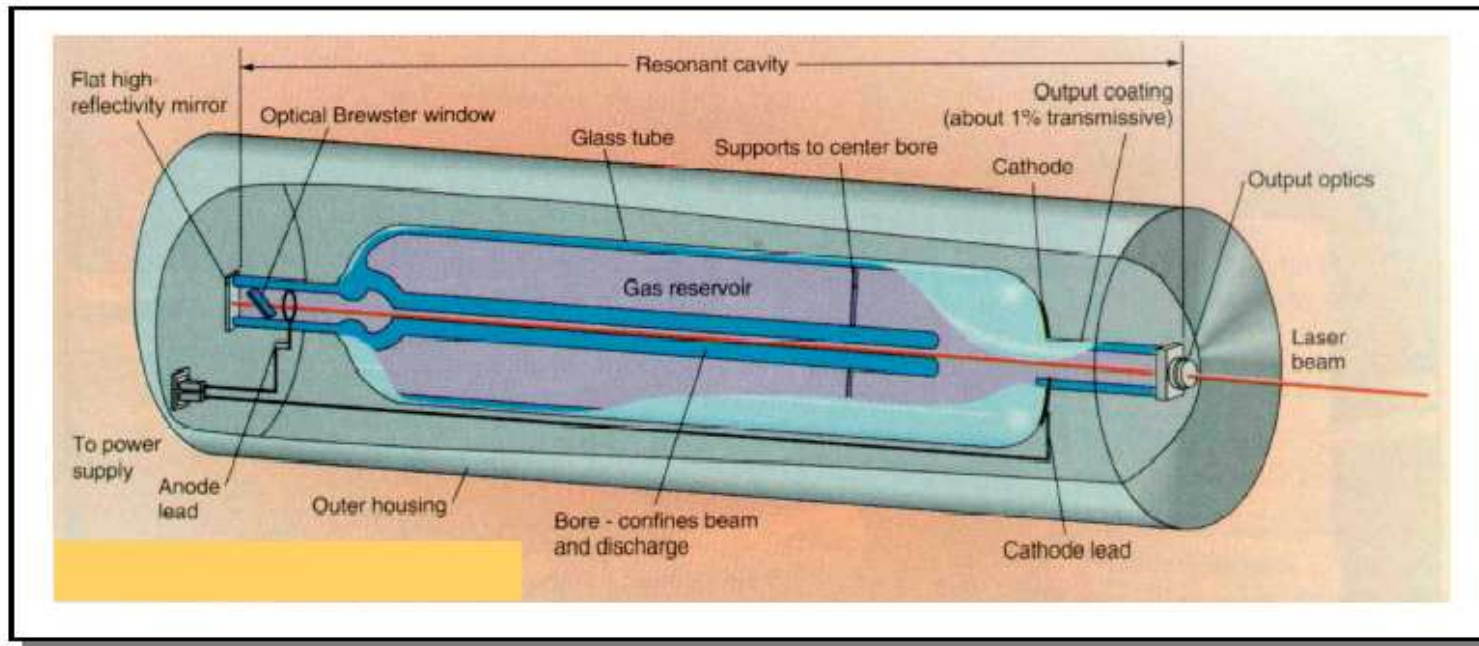
With relatively small gain, the output powers are not very high – only a few mW. However, the ease of manufacture makes these extremely common lasers for low power applications: bar-code readers, laser alignment tools (theodolites, rifle sights), classroom demos etc. They are gradually being replaced nowadays by visible semiconductor laser diodes, which are commonly used in laser pointers.



### Helium neon wavelengths and power levels

Wavelength (nm)	Maximum power (mW)	Gain (relative to 632.8 nm)
543.5	1.5	1/17
594.1	7.0	1/15
604	2.5	1/10
611.9	7.0	1/5
629	-	1/5
632.8	75	1
635	-	1/8
640.1	1.5	1/5
730.5	0.3	1/8
1152.6	17.5	4/5
1523.5	1.5	-
2396	0.5	-
3392.0	24	44/1

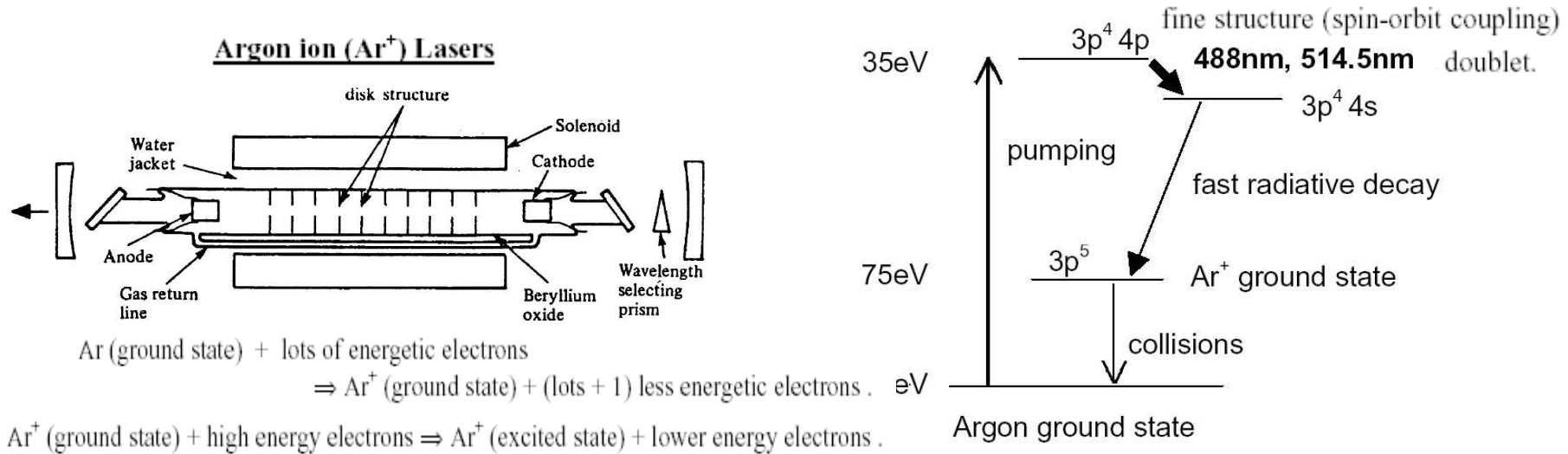
from Yariv, Q.E.



- ❖ Gas: helium-neon mixture ( $p_{\text{tot}} \sim 1$  torr;  $p_{\text{Ne}}:p_{\text{He}} \sim 1 : 5 \dots 12$ )
- ❖ Wavelength selection by mirror coatings and choice of discharge parameters
- ❖  $\lambda = 632.8$  nm most important, 1 - 5 mW
- ❖ Several million lasers sold, 1000 mk /tube + current supply (x2)

## Related lasers: Helium cadmium

The population inversion scheme in HeCd is similar to that in HeNe's except that the active medium is  $\text{Cd}^+$  ions. The laser transitions occur in the blue and the ultraviolet at 442 nm, 354 nm and 325 nm. The UV lines are useful for applications that require short wavelength lasers, such as high precision printing on photosensitive materials. Examples include lithography of electronic circuitry and making master copies of compact disks.



Argon has 18 electrons with the configuration  $1s^2 2s^2 2p^6 3s^2 3p^6$ . Argon atoms incorporated into a discharge tube can be ionized by collisions with the electrons. The  $\text{Ar}^+$  ion has 17 electrons. The excited states of the  $\text{Ar}^+$  ion are generated by exciting one of the five 3p electrons to higher levels. The level scheme is given below. The important transitions occur between the 4p and 4s levels of the  $\text{Ar}^+$

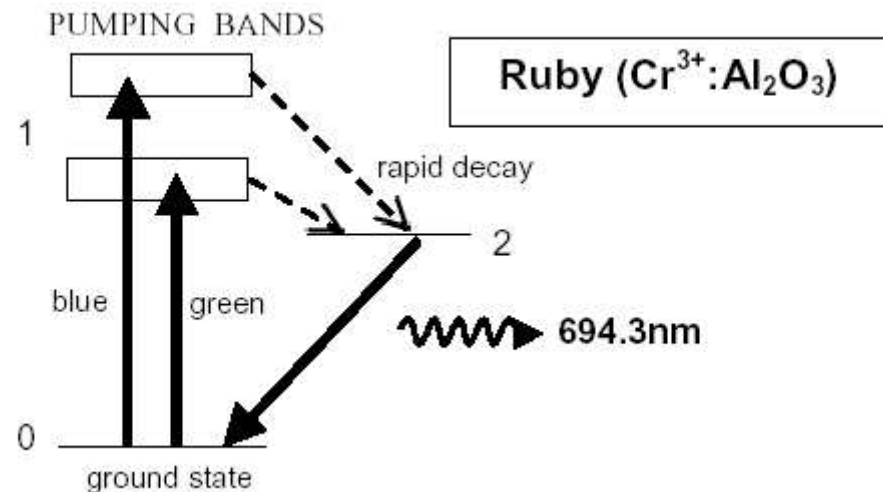
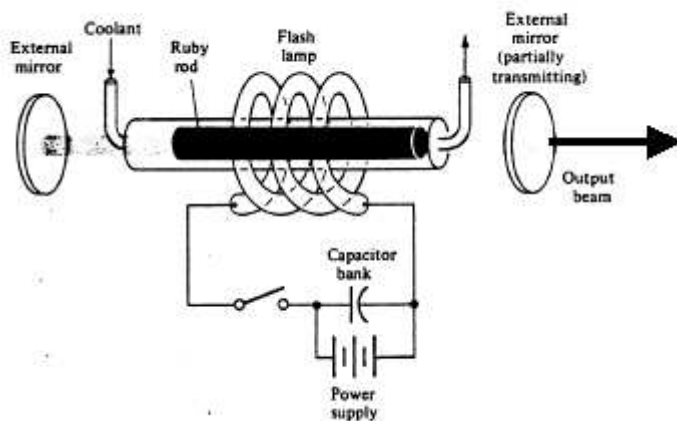
The diagram above shows a typical arrangement used in an  $\text{Ar}^+$  laser. Argon lasers tend to be much bigger than HeNe's. The tube length might be 1–2 m, and the tube might be running at 50 A with a voltage of 250 V. Hence water-cooling is necessary. Output powers up to several tens of Watts are possible. The tube is enclosed in a magnet. The magnet is required to contain the  $\text{Ar}^+$  ions from deflections by stray fields. The ends of the tube are cut at Brewster's angle to reduce reflection losses. A prism selects the emission line that is to be used.

In addition to laser light shows, argon lasers are used for pumping tunable lasers such as dye lasers and Ti:sapphire lasers. There are also some medical applications such as laser surgery, and scientific applications include fluorescence excitation and Raman spectroscopy.

## Ruby

Ruby lasers have historical importance because they were the first successful laser to operate. Ruby consists of  $\text{Cr}^{3+}$  ions doped into crystalline  $\text{Al}_2\text{O}_3$  (sapphire) at a typical concentration of around 0.05% by weight. The  $\text{Al}_2\text{O}_3$  host crystal is colourless. The light is emitted by transitions of the  $\text{Cr}^{3+}$

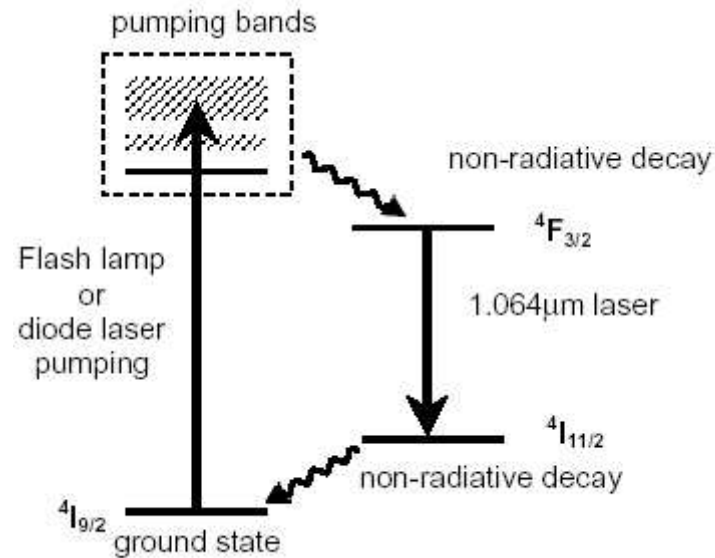
The diagram below shows a typical arrangement. The crystal is inserted inside a powerful flashlamp. Water-cooling prevents damage to the crystal by the intense heat generated by the lamp. Mirrors at either end of the crystal define the cavity. The lamps are usually driven in pulsed mode by discharge from a capacitor bank. The pulse energy can be as high as 100 J per pulse. This is because the upper laser level has a very long lifetime (3 ms) and can store a lot of energy.



Ruby has strong absorption bands in the blue and green spectral regions (hence the red colour). Electrons are excited to these bands by a powerful flashlamp. These electrons relax rapidly to the upper laser level by non-radiative transitions in which phonons are emitted. This leads to a large population in the upper laser level. If the flashlamp is powerful enough, it will be possible to pump more than half of the atoms from the ground state (level 0) to the upper laser level (level 2). In this case, there will then be population inversion between level 2 and level 0, and lasing can occur if a suitable cavity is provided. The laser emission is in the red at 694.3nm.

## Nd:YAG & Nd:glass

Neodymium ions form the basis for a series of high power solid state lasers. In the two most common variants, the  $\text{Nd}^{3+}$  ions are doped into either Yttrium Aluminium Garnet (YAG) crystals or into a phosphate glass host. These two lasers are known as either Nd:YAG or Nd:glass. The main laser transition is in the near infrared at  $1.06\ \mu\text{m}$ . The wavelength does not change much on varying the host.



The diagram above shows the level scheme for the  $\text{Nd}^{3+}$  lasers, which are *four-level lasers*. Electrons are excited to the pump bands by absorption of photons from a powerful flashlamp or from a diode laser operating around 800 nm. The electrons rapidly relax to the upper laser level by phonon emission. Lasing then occurs on the  $^4F_{3/2} \rightarrow ^4I_{11/2}$  transition. The electrons return to the ground state by rapid non-radiative decay by phonon emission.

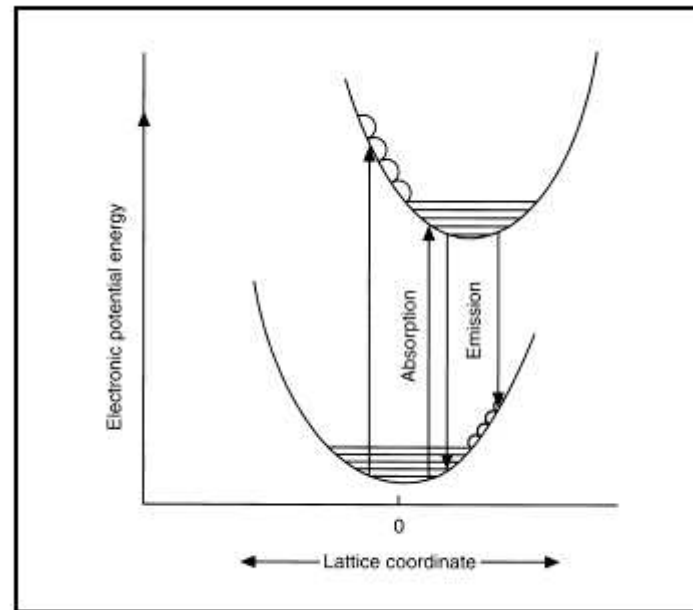
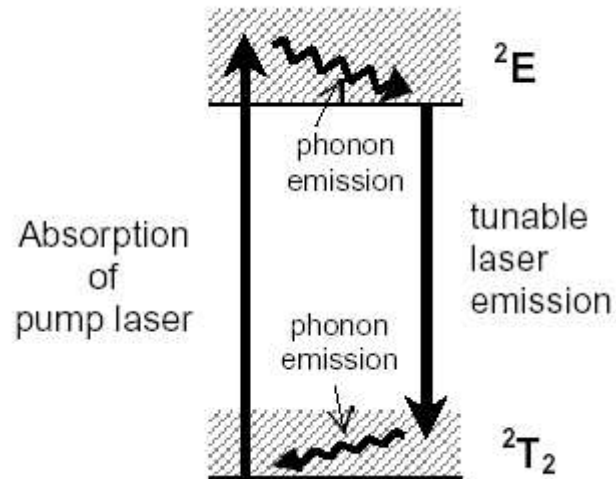
## Ti:sapphire

Titanium-doped sapphire lasers represent the current state-of-the-art in tunable lasers. The level scheme is shown below.

### Laser crystal:

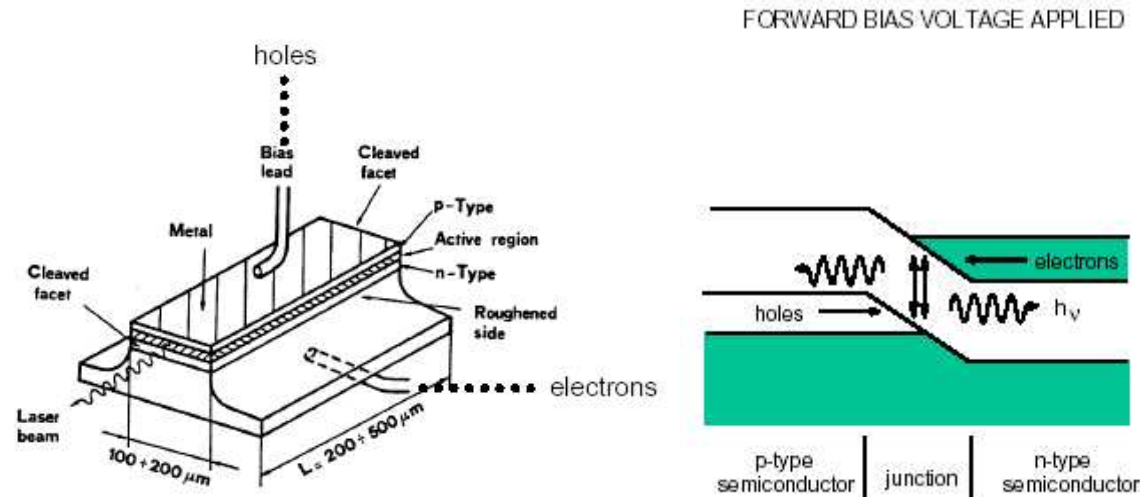
$\text{Ti}_2\text{O}_3$  (0.1% - 0.5%) in  $\text{Al}_2\text{O}_3$  (sapphire)

- ✓ pumping with Ar laser or frequency-doubled diode-laser-pumped Nd:YAG
- ✓  $P_{\text{cw}} \rightarrow 50 - 100 \text{ W}$
- ✓ wavelength tunability  $\Delta\lambda$ : 660 nm – 1180 nm



## Semiconductor Diode Lasers

These are by far the most common types of lasers. They are used in laser printers, compact disc players, laser pointers, and optical fibre communication systems. The laser consists of a semiconductor p-n diode cleaved into a small chip. Electrons are injected into the n-region, and holes into the p-region. The electrons and holes recombine in the active region at the junction and photons are emitted. The laser cavity is formed by using the cleaved facets of the chips. The refractive index of a typical semiconductor is in the range 3–4. This gives about 30% reflectivity at each facet. This is enough to support lasing, even in crystals as short as  $\sim 1$  mm, because the gain in the semiconductor crystal is very high.



The energy of the photons emitted is equal to the bandgap of the semiconductor. The semiconductor must have a *direct band gap* to be an efficient light emitter. Silicon has an indirect band gap, and is therefore not good for laser diode applications. The laser diode industry is based mainly on the compound semiconductor GaAs. This has a direct band gap at 1.4 eV (890 nm). By using alloys of GaAs, the band gap can be shifted into the red spectral region for making laser pointers, or further into the infrared to match the wavelength for lowest losses in optical fibres (1500 nm). Very recently the short wavelength emission limit has been extended into the blue by using the wide band gap III-V semiconductor GaN in the active region.

The power conversion efficiency of electricity into light in a diode laser is very high, with figures of 25% typically achieved. This compares with typical efficiencies  $< 0.1\%$  in gas lasers. Since the laser chips are so small, it is possible to make high power diode lasers by running many GaAs chips in parallel. Laser power outputs over 20W can easily be achieved in this way. These high power laser diodes are very useful for pumping Nd:YAG lasers.



Laser-Literatur im WWW (jeweils viele pdf-Dateien):

Kurs Laserphysik :

[http://metrology.hut.fi/courses/Laser\\_physics2002/](http://metrology.hut.fi/courses/Laser_physics2002/)

Kurs Laser Technology and Optics:

[http://waist.hut.fi/opetus/l\\_o2000/luennot/kalvot.html](http://waist.hut.fi/opetus/l_o2000/luennot/kalvot.html)

Kurs Lasers

<http://www.stanford.edu/class/ee231/>

Kurs Atomic and Laser Physics

(Laserphysikskript ganz unten auf der Webseite)

<http://www.shef.ac.uk/uni/academic/N-Q/phys/teaching/phy332/>

Online-Tutorial:

<http://www.ilt.fhg.de/ger/lasertutorial.html>

Detection systems are made possible by a few basic types of light-to-electrical signal conversion processes. Optical detector systems can be roughly divided into:

- Thermal detectors
- Photon detectors

### RESPONSIVITY (S)

$$S = \frac{Y}{X}$$

Where:

Y = detector output

X = radiation input

Examples of Y include current or counts from a photomultiplier or voltage from a thermopile. Y usually has a value  $Y_0$  (dark signal) for  $X = 0$ . In this case

$$S = \frac{(Y - Y_0)}{X}$$

X can be any radiative input. The units of X are usually watts or lumens. In cases of uniform irradiance on the detector, X may be given as the product of the irradiance and detector area.

S is usually wavelength dependent. The variation with wavelength is described by the Spectral Responsivity  $S(\lambda)$

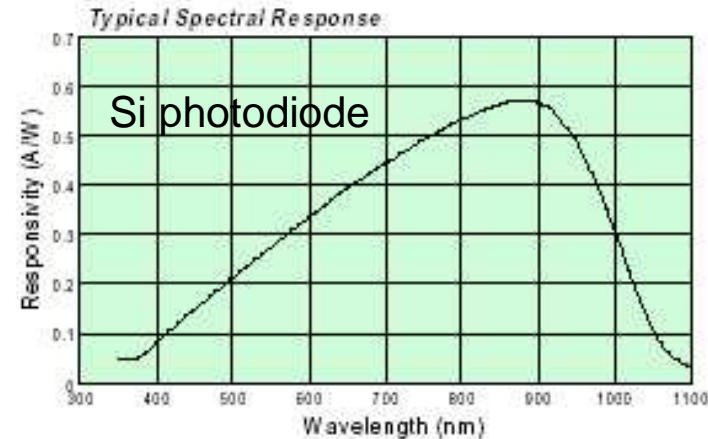
$$S(\lambda) = \frac{dY(\lambda)}{dX(\lambda)}$$

Where:

$dY(\lambda)$  = the fraction of output due to input  $dX(\lambda)$  at  $\lambda$

### RESPONSE TIME ( $\tau$ )

$\tau$  is the time it takes a detector's output to rise when suddenly subjected to constant irradiance. When the irradiance is turned off, the detector output falls to  $1/e$  of the initial value in one time constant. The rise and fall time constants are frequently different, since different physical parameters may cause them.



### NOISE EQUIVALENT POWER (NEP)

NEP is the radiant flux in watts necessary to give an output signal equal to the r.m.s. noise output from the detector. The flux may be either continuous or sinusoidally modulated.

The response is assumed to be linear down to the noise level. NEP values should be stated at a specified wavelength, modulation frequency, detector area, temperature and detector bandwidth. Detector bandwidth is usually normalized to 1 Hz and NEP is frequently quoted in watts  $\text{Hz}^{-1/2}$ .

NEP is the most commonly used version of Noise Equivalent Detector Input ( $P_N$ ).

### DETECTIVITY (D)

D is the reciprocal of NEP. It is given by:

$$D = \frac{1}{\text{NEP}}$$

This gives a figure of merit which is larger for more sensitive detectors.

## THERMAL DETECTORS

Thermal detectors work by converting the incident radiation into a temperature rise. The temperature change can be measured in several ways. Our detectors use either the voltage generated at the junction of dissimilar metals, or the pyroelectric effect. In either case, we have a "sensitive element" where we measure temperature change.

We offer two types of Thermal Detectors:

1. Thermopile Detectors for DC radiation.
2. Pyroelectric Detectors for pulsed, chopped or modulated radiation.

## THERMOCOUPLES

Radiation detecting thermopiles are based on thermocouples. A thermocouple consists of two dissimilar metals connected in series. To detect radiation, one junction is blackened to absorb the radiation. The temperature rise of the junction (with respect to another non-irradiated junction) generates a voltage. This effect, discovered by Seebeck, is the basis of all thermocouple temperature sensors.

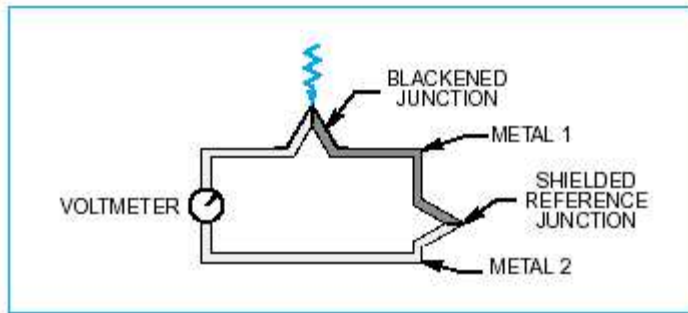
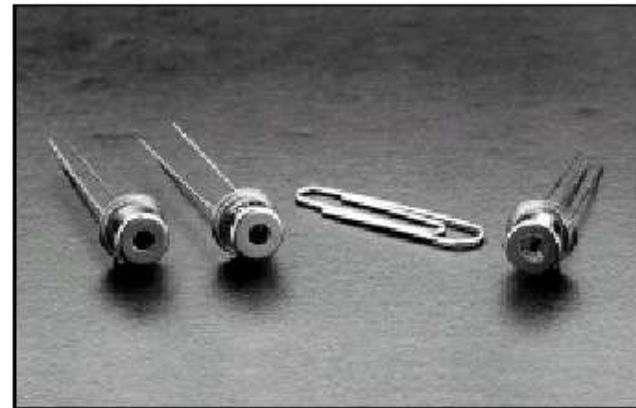


Fig. 4 Principle of operation of a thermocouple detector. The dissimilar metals 1 and 2 are often bismuth and antimony. The sensing junction usually has a thin blackened metal foil attached to absorb more radiation. The other junction is shielded.

## Thermopiles

One way to increase the output voltage is to connect a number of the thermocouple junctions (typically 20 to 120) in series. All the "hot" junctions are placed close together to collect the radiation. This constitutes a thermopile.



Thermopile Detectors.

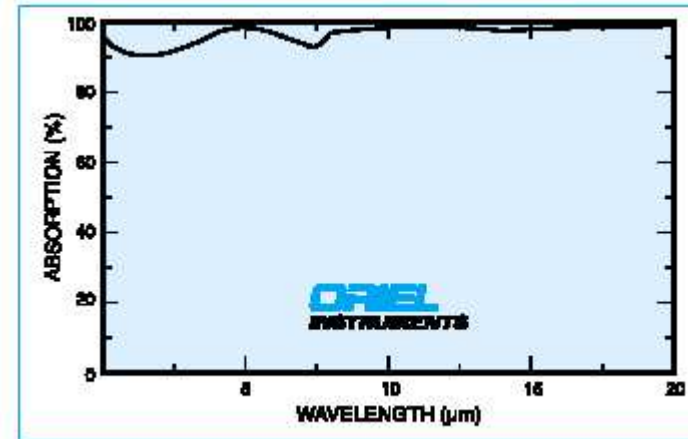


Fig. 1 Absorption of our Thermopile Detector coating.

Table 1 Window Specifications

Material	Usable Spectral Range (μm)	Approx. Transmittance (%)	Water Solubility (g/100 g)	Affected By Humidity
Calcium Fluoride (CaF <sub>2</sub> )	0.13 to 11	94	0.0017	No
Sapphire	0.15 to 6	90	0.0	No
KRS-5	0.6 to 40	74	0.05	No

## Pyroelectric Detectors

A pyroelectric material has electric polarization even in the absence of an applied voltage. The materials are usually crystalline. On heating, the material expands and produces a change in the polarization which builds up a charge on opposite surfaces. This causes a current to flow in the circuit which connects the surfaces.

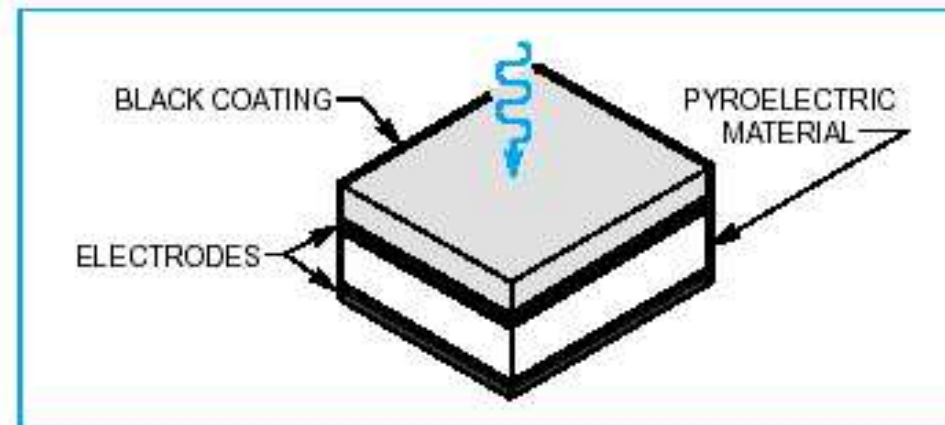


Fig. 6 Schematic drawing of a pyroelectric detector.

# Junction Photodiodes

## Silicon Photodiodes

Silicon photodiodes are the most common detectors of light used in instrumentation. The spectral response (Fig. 8 on page 6-6) covers the UV, the visible and the near infrared. The linearity and dynamic range are excellent (Fig. 1 on page 6-2); getting a signal is simple.

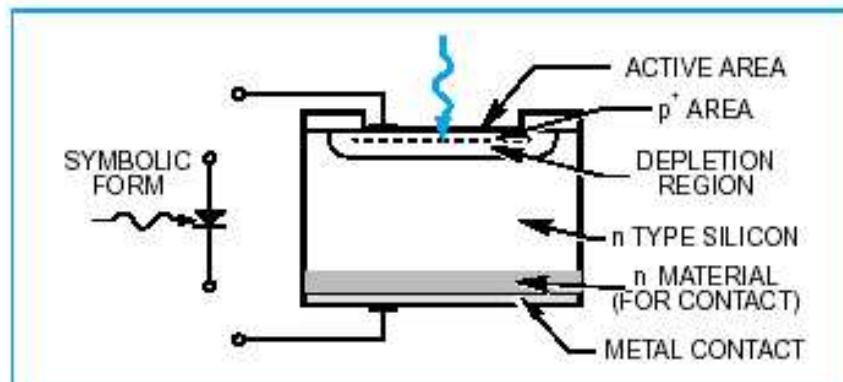


Fig. 10 Model of a silicon photodiode. The junction between the p<sup>+</sup> and depletion regions give this detector its name.

## PHOTOCONDUCTIVE DETECTORS

In photoconductive detectors, absorbed incident photons produce free charge carriers. These change the electrical conductivity of the detector. An applied voltage, or bias, causes a current to flow which is proportional to the photon irradiance (it helps if the dark resistance is very high). Lead sulfide and lead selenide are examples of this type of detector. Fig. 13 shows this concept.

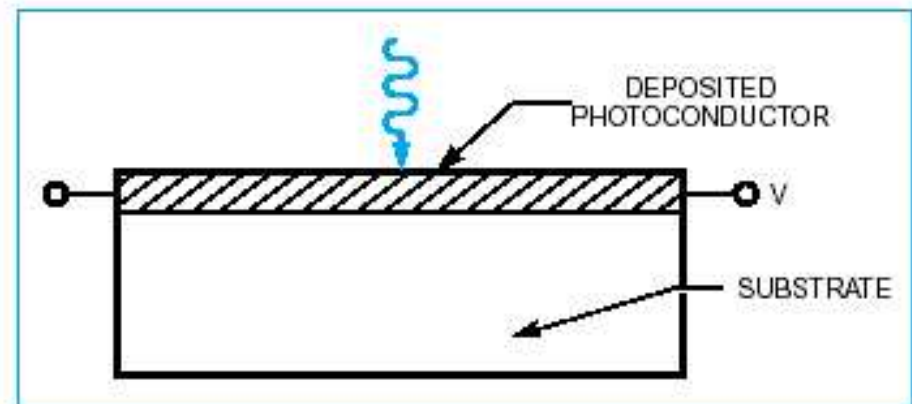


Fig. 13 Schematic of a photoconductive detector.

## PHOTON DETECTORS

Photon or Quantum detectors respond to the incoming photon flux in a quantized manner. They produce, under perfect conditions, a single response element for a single photon. Of course, perfect conditions are not usually found in nature, therefore you must account for insufficiencies of response.

## PHOTOEMISSIVE AND SEMICONDUCTOR JUNCTION DETECTORS

### Common Characteristics

Photoemissive and semiconductor detectors have much in common.

1. The direct photo-electron interaction is very rapid so these detectors have the potential of following fast changing radiation levels.
2. Detectivity is in general higher than that of thermal detectors, but over a limited wavelength range.
3. All the detection mechanisms are wavelength dependent; i.e. there is a peak in responsivity with a fall off at both long and short wavelengths (Fig. 8). The long wavelength (low photon energy) cut-off occurs because there is a certain minimum photo energy required to cause photo emission, to produce charge carriers, or to generate hole-electron pairs.

The short wavelength cut-off is a function of two effects:

1. The responsivity in terms of power drops off because there are fewer short wavelength photons per watt, see Fig. 7.
2. At the extreme short wavelength end, the energetic photons may no longer be absorbed in the sensitive region. In the deep ultraviolet, absorption of the photons before they reach the sensitive region is also a problem. Detector windows, or surface coatings can also contribute to the spectral shape of the responsivity curve.

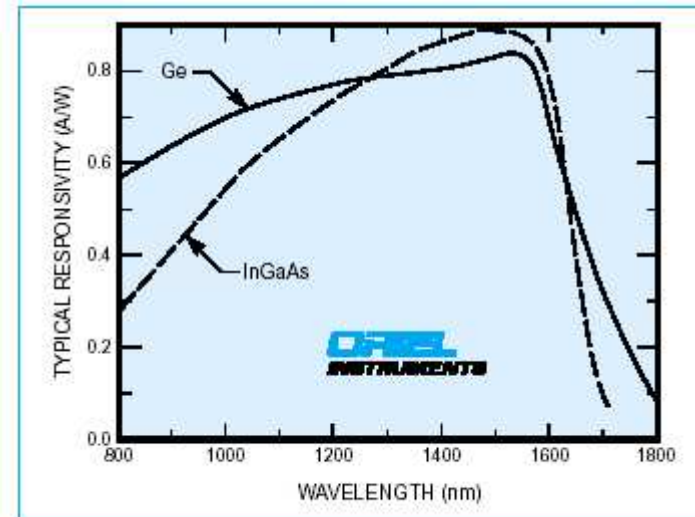


Fig. 1 Typical responsivity of InGaAS and Ge Detectors.

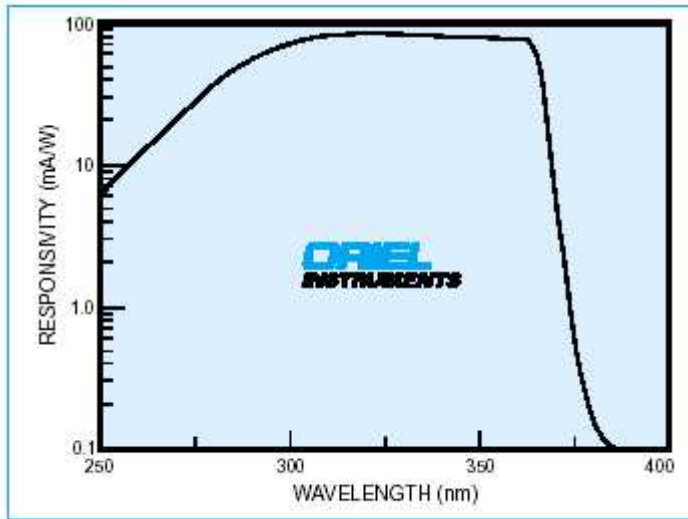


Fig. 1 Typical responsivity of solar blind GaN Detectors.

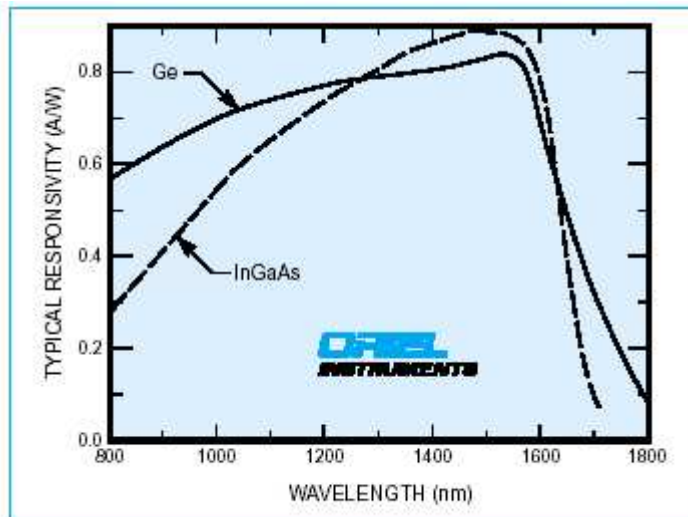


Fig. 1 Typical responsivity of InGaAs and Ge Detectors.

These **new** GaN Schottky barrier devices offer excellent performance in the UV, even in the presence of high levels of visible or infrared radiation. This is because their responsivity drops by three orders of magnitude, above 400 nm.

#### InSb

These liquid Nitrogen cooled detectors, used with our FT-IR instruments, on page 5-19, offer ultimate performance in the 2 to 5  $\mu\text{m}$  range.

#### Ge, InGaAs, Extended InGaAs Photodiodes

Just about everything we said about silicon detectors can also be said about these diodes. They find most applications in the NIR, 0.8 to 2.5  $\mu\text{m}$ . Their noise performance does not match that of Si and therefore we offer TE cooled versions of them, besides the room temperature ones.

#### HgCdZnTe Photodiodes

Things get even more confusing as far as junction photoconductors vs bulk photoconductors with these small band gap IR photodetectors. However, at least one room temperature implementation of these detectors does function in a photovoltaic mode and thus deserves to be listed in this section. Their current biased versions fit better with the PbS and PbSe photoconductors than with back biased junction diodes. Therefore we talk about them a little more in that section, page 6-75.

We offer these detectors for the 2 to 12  $\mu\text{m}$  wavelength range. Optical immersion is offered with most of them to take better advantage of the detector active area.

Semiconductor photon detectors, such as the PbS and PbSe, have a small energy gap making them sensitive to infrared radiation. Unfortunately, when these detectors are operated at room temperature, the thermal energy present in the detector can excite charge carriers as well as infrared photons, creating a significant source of background signal indistinguishable from the infrared signal. The classic solution to rid the signal of this background interference is to use an optical chopper to modulate the infrared signal.

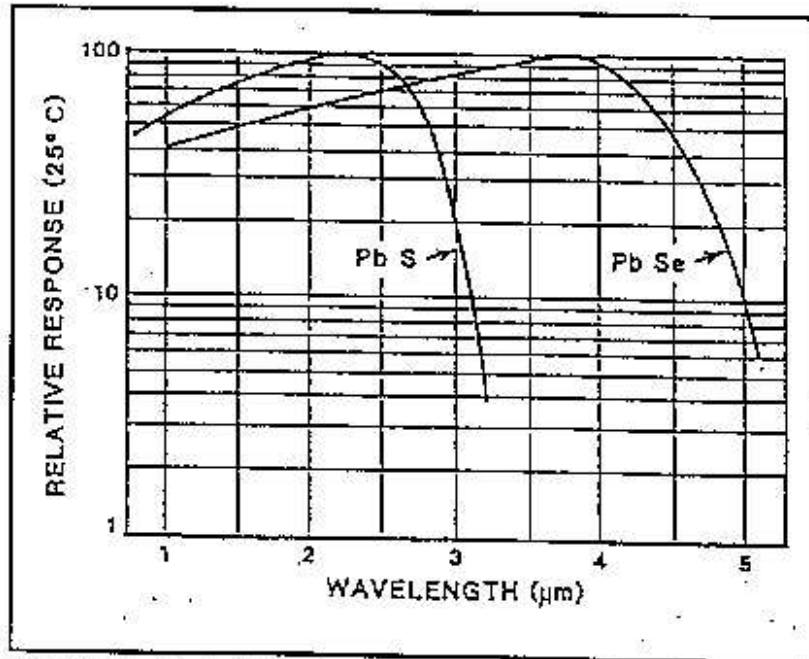


Figure 1 - Variation of response with wavelength for PbS and PbSe detectors.

The chopper also provides a reference signal (the chopper modulation frequency) with which to synchronize ("lock-in") the detection electronics. Only the signal present at the chopper frequency is amplified and the DC background signal is filtered out. This technique, known as "lock-in detection", is commonly used to reduce signal drift from thermal noise sources inherent in DC detection systems. The background signal from the thermal excitation of the bulk semiconductor also has some broadband noise associated with it; the lock-in detection technique limits the output noise to a very narrow frequency band centered at the optical chopper frequency and subtracts the background signal.

### Chopper - Zerhacker

Das Bild rechts zeigt verschiedene Chopperräder, die mit dem Steuergerät auf eine bestimmte Frequenz eingestellt werden können.





## Photomultiplier Tubes, PMTs

In a photoemissive detector, light interacts directly with the electrons in the detector material. An absorbed photon frees an electron and the surplus energy gets converted into kinetic energy of an electron. Electrons with enough kinetic energy escape from the surface. The electrons emitted in this way produce the cathode photocurrent in photomultiplier tubes. An applied voltage causes the electrons to flow toward the anode, creating a current that can be proportional to light intensity over 6 to 8 orders of magnitude. The electron multiplier part of a photomultiplier tube amplifies the photocurrent by secondary emission. This is a low noise process which produces currents that are orders of magnitude larger than the initial photocurrent. Photomultipliers are more sensitive than any other detector in the near UV and visible regions. See pages 6-66 and 6-67 for photomultiplier tube specifications.

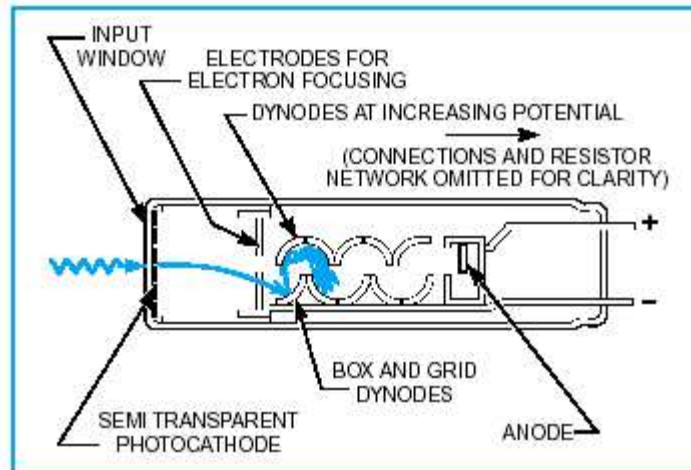


Fig. 9 Schematic of a photomultiplier tube.



Photomultiplier Tubes in 70680 and 77265 PMT Housings.

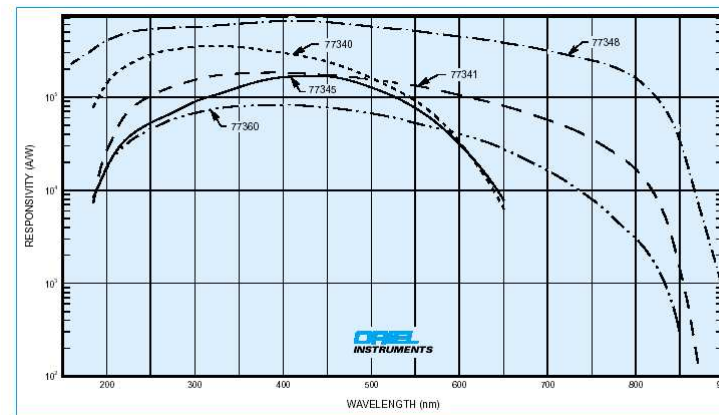


Fig. 2 Typical Responsivity of Photomultiplier Tubes at the supply voltages specified below.

### TECH NOTE

PMTs can be damaged by exposure to excessive light levels in the presence of bias voltage. This is due to anode damage by high current densities. Opening your optical set-up while the PMT is biased can easily lead to a need for an expensive replacement tube. Please note the maximum DC anode currents in the table above (averaged over any 30 s time interval), and make sure they are not exceeded in your standard set-up. For pulsed applications you can draw up to 50 X higher currents for short times, as long as average current ratings are not exceeded.

The photocathodes of PMTs are very light sensitive. Their noise behavior is negatively affected by exposure to strong light, even in the absence of bias voltage, and may take some time to recover once they are screened from light. Typically more than half an hour is required for recovery. You may need several hours to return to the lowest noise levels.