An Apparatus for the Fabrication of Large Area Hybrid Photo-Diodes

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Abstract

This note describes a new facility for the fabrication of large area Hybrid Photo-Diodes which are intended to be used in the RICH detectors of the LHCb experiment. The facility, which is currently in the commissioning phase, has two main functions: processing of a photocathode in an external process, and subsequent encapsulation of the vacuum tube with a base plate on which the silicon detector is pre-mounted. For the best protection of the photocathode and the silicon detector a cold indium sealing technique is being developped.

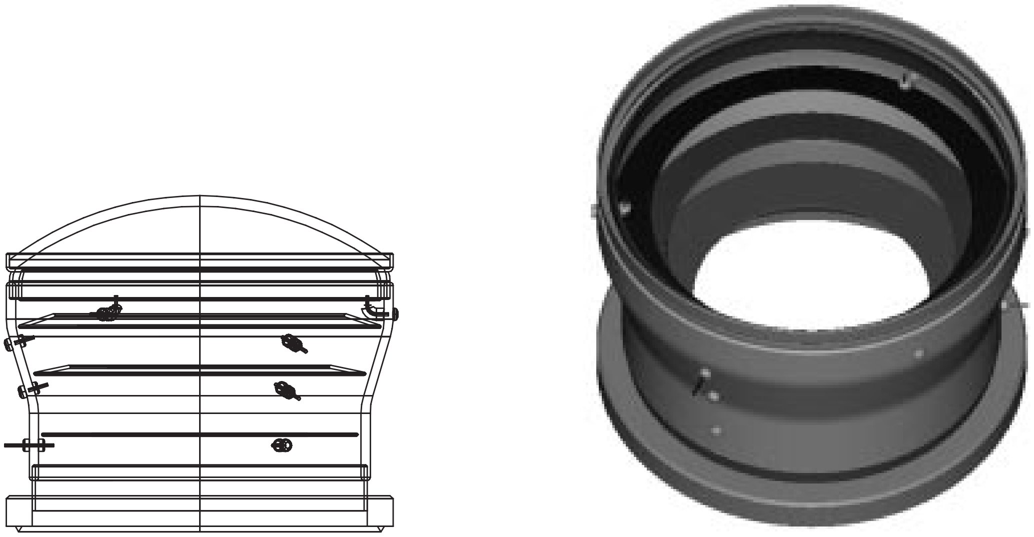

Figure 1: Cross-section and 3D-view of the large area HPD prototype.

1 Introduction

1.1 The large area HPD for the LHCb RICH detectors

The LHCb spectrometer includes two Ring Imaging CHerenkov (RICH) detectors for π/K separation in the momentum range 1 - 150 GeV/c [1, 2]. The RICH station close to the interaction region (RICH 1) covers the angular region $25 < \theta < 330$ mrad. It is equipped with two different radiator media: aerogel and C_4F_{10} gas. The second RICH station behind the LHCb magnet (RICH 2) provides a smaller angular acceptance ($10 < \theta < 120$ mrad) and uses CF_4 as radiator medium.

The Cherenkov light is focused by means of spherical mirrors onto detection planes outside the acceptance of the LHCb spectrometer. In the current detector geometry the detection planes of the two RICH stations represent a total surface of almost 3 m^2 for which single photon detection with a granularity of about 2.5×2.5 mm^2 is required. Assuming hexagonal close packing of round photo detectors and an active surface coverage of 80%, the corresponding total number of channels is about 500,000.

Hybrid Photo-Diodes (HPD) are photodetectors consisting of a photocathode and a silicon detector encapsulated in an UHV vacuum tube. The photocathode is deposited on the inner side of the entrance window of the vacuum tube, and the silicon detector is normally mounted on the base plate of the housing. HPD's combine the sensitivity and speed of photomultipliers with the spatial and energy resolution of silicon detectors. Commercially available HPD's have only few pixels and small active area. Each pixel is individually fed through the base plate. In order to meet all requirements for photo detectors for the LHCb RICH detectors, specific R&D for HPD's is required.

A comprehensive R&D programme [3] has been launched to develop large area HPD's adequate for the LHCb requirements. One branch of the programme focuses on the development of a HPD with 5" (127 mm) diameter. The geometry of this HPD is shown

in Figure 1. The HPD will be produced with a bialkali photocathode (K_2CsSb) which is appropriate for the required performance in the LHCb RICH detectors. A quantum efficiency of close to 30% is expected at the peak wavelength of 400 nm. The silicon detector[1] comprises 2048 pads each with a surface of 1 mm^2. In this design the detector signals are amplified and sampled by 16 VA3[2] chips [4] which are mounted on a ceramic carrier inside the vacuum envelope. The number of feedthroughs through the base plate can so be reduced to about 50. The glass envelope is welded to a stainless steel flange with a knife edge which fits into the V-shape groove on the base plate.
In this paper we describe the facility which we have designed to process the photocathode and to subsequently encapsulate the vacuum envelope with the base plate which carries the pre-mounted silicon detector. The facility is currently in the commissioning phase.

1.2 General considerations on HPD fabrication

HPD's have to be operated under excellent vacuum conditions. Typical values reported in the literature lie in the range $10^{-7} - 10^{-8}$ Pa ($10^{-9} - 10^{-10}$ mbar). Collisions of the fast electrons with atoms of the residual gas create ions which are accelerated back onto the photocathode. Feedback induced noise and a continuous degradation of the cathode efficiency will be the consequences. In order to reach these vacuum conditions the deposition apparatus including the envelope and the silicon detector have to undergo a bake out cycle at temperatures up to 300^{o}C.

HPD's can be produced in two basically different types of processes.

- **Internal processes:** The silicon detector is mounted inside the vacuum tube before the photocathode is deposited. The evacuated glass tube is closed except of small lateral pipes through which small evaporation sources can be inserted. These openings are afterwards sealed off by melting the glass. This technique is widely used for photo-multiplier fabrication.

- **External processes:** There are two main variants of external processes.
  1.) The photocathode is first deposited on a separated window. The window is then used to seal the vacuum tube which contains already the silicon detector.
  2.) The vacuum tube has a removable bottom plate. The photocathode is deposited onto the top window through the bottom hole. The tube is afterwards sealed off by means of the base plate which carries the silicon detector.

We decided to adopt an external process in its second variant. Compared to the internal processes it has the essential advantage of avoiding the risk of contaminating the silicon detector during the photocathode processing. Particularly Cesium, once diffused in the silicon surface, is known for its negative influence on the detector performance. The thermal load on the silicon detector during the evaporation is another drawback of the internal processes. The external process provides in general more flexibility and freedom during the photocathode processing. The evaporation sources can be positioned exactly in the centre of curvature of the HPD window, which improves the uniformity of the photocathode.

[1]The silicon detectors are being fabricated by SINTEF, N-7034 Trondheim, Norway.
[2]VA3 is a VLSI chip produced by Integrated Detector and Electronics AS (IDE AS), Gaustadalléen 21, N-0371 Oslo, Norway.

The sealing technique is another critical issue in the processes. The hot glass sealing technique used in the internal processes gives a risk of vacuum degradation due to uncontrolled outgasing. We employ a cold Indium sealing technique. In contrary to hot Indium techniques, where the joint is made with liquid Indium, the cold Indium technique is superior from the outgasing and thermal load point of view. The cold variant requires however comparably high forces between the two pieces to be sealed by the solid Indium. We have chosen a geometry where a knife-edge cuts into the surface of the Indium which fills a V-shaped groove on the HPD base plate. About 60 N/mm, i.e. 23 kN for a 380 mm long joint, are needed to form a UHV tight sealing.

2 Description of the apparatus

2.1 Mechanics and functionality

The apparatus (see Figure 2) consists of a cylindrical vacuum tank of about 290 l volume (diameter 690 mm, height 770 mm) with a removable lid. All parts are made of stainless steel or other ultra high vacuum compatible and heat resistant materials. The cylindrical part has been produced by rolling a flat plate and subsequent welding. All welds have been performed with the TIG process (Tungsten electrodes, welding under Argon atmosphere). Radiography was used to check the quality of all welded joints. The required vacuum quality demands the use of metal joints. The big joint for the lid and the one which seals the flange for the press mechanism are of the HELICOLFLEX type[3]. All other joints are of the standard COMFLAT knife edge type and use copper gaskets. All commercial components, like linear motion feedthroughs and electrical feedthroughs, are UHV compatible and stand bake out temperatures up to 300^{o}C.

In the centre of the vacuum tank an inner cylinder is installed which carries both the HPD glass envelope and four movable carriages. The glass envelope is held in the centre of a rigid cross shaped structure. Four different carriages can be moved under the centre of the HPD by acting on the linear motion feedthroughs. A view onto the inner cylinder is shown in Figure 3. Two of these carriages support the evaporation sources. One carriage is reserved for the HPD baseplate with the silicon detector. The fourth carriage is currently not used.

Once a carriage has been moved under the centre of the HPD envelope, it can be lifted by means of a piston which is driven by a motor via a threaded bar. This allows to position the evaporation sources in the centre of curvature of the spherical HPD front window. The lifting mechanism is also used to apply the required force to form the final Indium joint between the envelope and the baseplate. In this case the applied force (up to 25 kN) is measured from the elastic distortion of a set of pre-deformed precision washers.

2.2 The vacuum system

The quantum efficiency of bialkali photocathode strongly depends on the cleanliness of the substrate surface and the vacuum conditions during evaporation. In addition the pressure inside the HPD after the encapsulation is crucial for the lifetime of the photocathode.

[3]Carbone Lorraine, F-42029 Saint-Etienne.

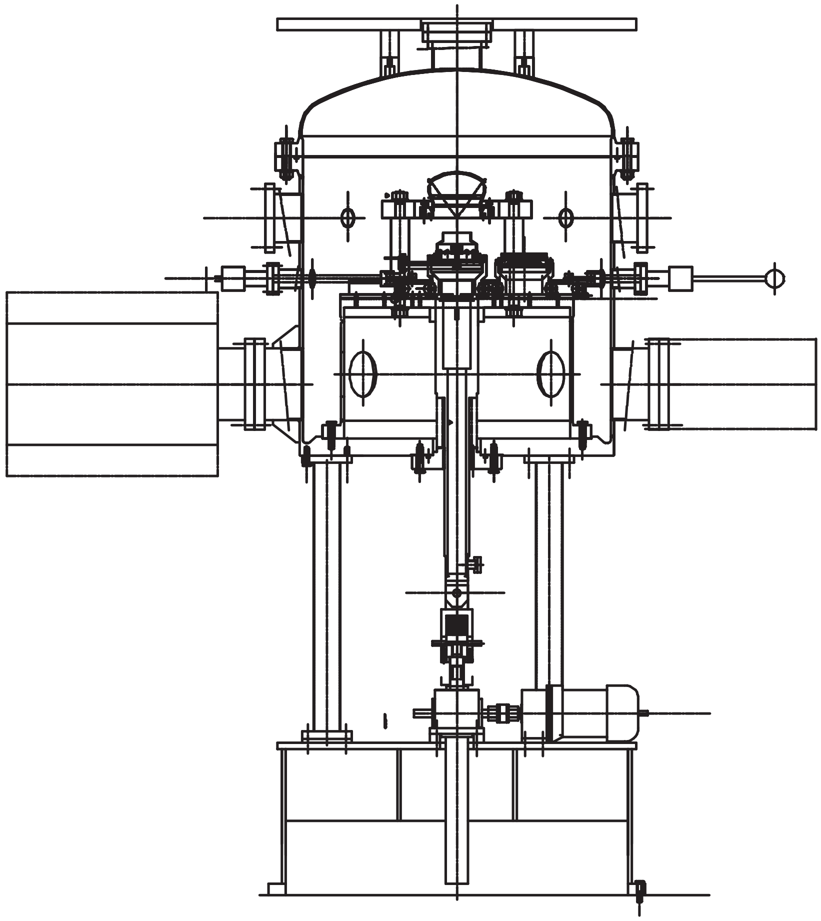

Figure 2: Side view of the deposition apparatus.

The vacuum system is designed for an ultimate pressure below 10^{-7} Pa. It comprises the following pumps

- rough vacuum pump: dry running scroll pump, 25 m^3/h
- turbo molecular pump, 600 l/s
- Titanium ion pump, 500 l/s

For maximum efficiency both the Titanium ion pump and the turbo molecular pump are connected directly to the vacuum tank. The vacuum tank is wrapped hermetically in a specially tailored heating jacket ($P_{total} = 3.7$ kW).

2.3 The laboratory

The deposition apparatus is installed in a dedicated clean laboratory equipped with the necessary infrastructure (crane, air condition, supply of Argon, Nitrogen, compressed air and water). The room is accessed via an air lock. A laminar air flow bench provides a local class 100 working environment and allows the HPD components and the evaporation sources to be prepared prior to installation in the vacuum system.

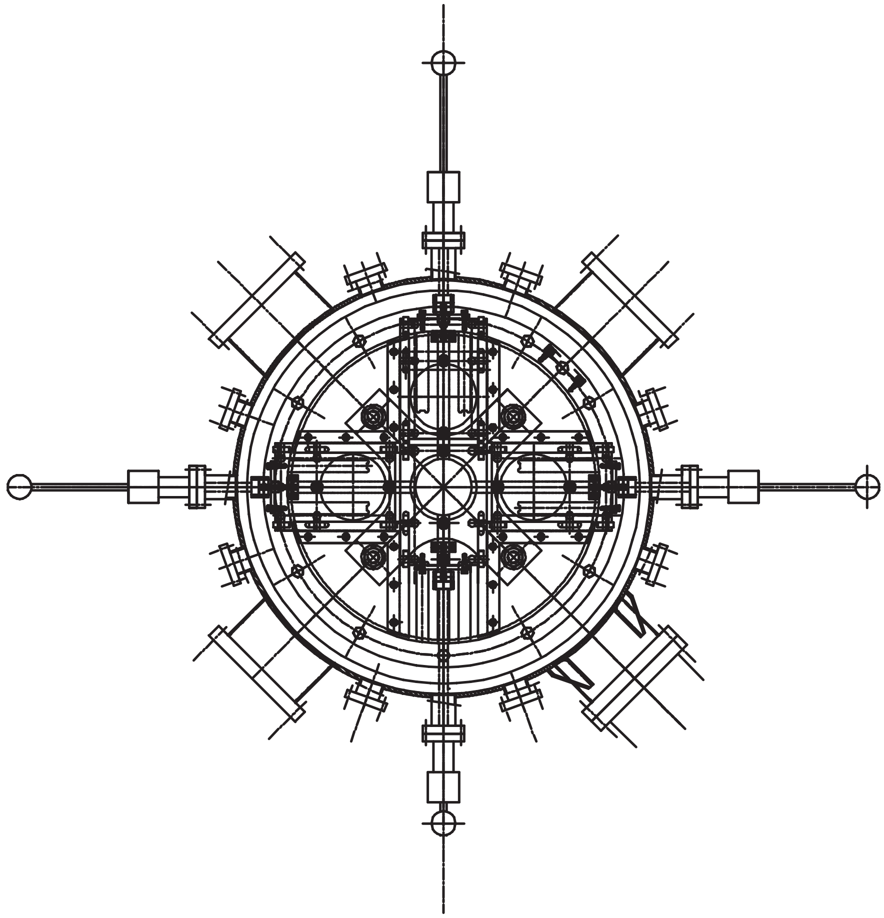

Figure 3: Cross section of the deposition apparatus.

3 Photocathode fabrication

3.1 The bialkali photocathode

The deposition apparatus has been designed to produce K_2CsSb bialkali photo cathodes by thermal evaporation. The typical spectral response of bialkali photo cathodes is shown in Figure 4.

The discovery of the favourable photoemissive properties of this material dates back to 1963 [5]. Semi-transparent and opaque bialkali cathodes are widely used in photomultipliers and recently also as fast electron sources for accelerators [6, 7].

3.2 The deposition process

The deposition set-up provides four independent evaporation stations. One carriage is equipped with a high current station (≤ 60 A) which is designed for evaporation of Antimony out of a wound Tungsten filament. The other three stations are placed next to each other on another carriage. They are designed for low current evaporation (≤ 10 A) of the alkali metals Potassium and Cesium from special dispensers[4]. In the dispenser the pure

[4]SAES GETTERS S.pA., I-20151 Milano, Italy

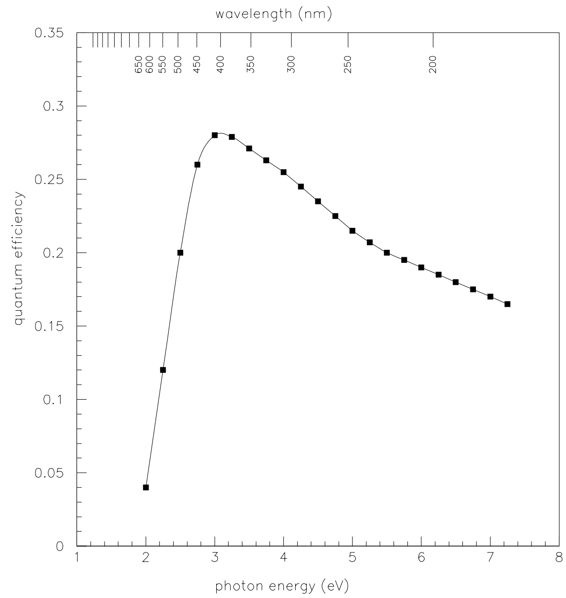

Figure 4: Typical quantum efficiency of a bialkali photocathode.

alkali metal is created by a thermally initiated reduction reaction of Cs_2CrO_4 or K_2CrO_4 with a reducing agent, consisting of a Zirconium-Aluminium alloy. The evaporated alkali metal escapes through a small slit on the top side of the dispenser. The evaporation rate is determined by the current through the sources.

During the various evaporation steps, the substrate, i.e. the HPD glass envelope has to be kept at well defined temperatures. Therefore the envelope is surrounded by a heating coil which is shielded on the outer side.

Various not well standardised recipes exist for the fabrication of the cathode [8, 9, 10, 11]. The bialkali photocathode can be fabricated via either K_3Sb or Cs_3Sb as intermediate step. Our apparatus provides the possibility to investigate both procedures.

In Figure 5 the process via the intermediate compound K_3Sb is shown schematically . First the Antimony layer is formed while the substrate is held at temperature of approximately 160^oC. The evaporation is stopped when the transmission of visible light through the Sb layer is reduced by about 30%. This corresponds to a thickness of the order of 100 Å.

In the next step a Potassium-Antimony photocathode is formed by exposing the Sb film to K vapour at a substrate temperature of 130^oC. The aim is to produce a compound with the composition K_3Sb, which may reach a peak quantum efficiency at 320 nm of about 5%. Therefore the quantum efficiency has to be monitored online and the evaporation stopped at the peak value.

Finally Cesium is evaporated at the same temperature and partially replaces the Potassium so that the cathode with the composition K_2SbCs is produced. The correct stoitchiometric ratio has again to be found by monitoring the quantum efficiency. A significant excess of Cesium will drastically reduce the quantum efficiency.

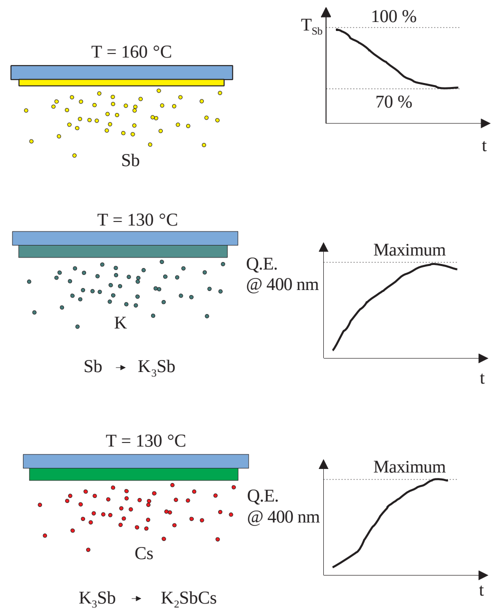

Figure 5: Schematic representation of the bialkali deposition process.

3.3 Control and monitoring

The control and monitoring of the evaporation process is essential to reach high and reproducible quantum efficiencies. The substrate temperature is one of the crucial parameters in the deposition process. An elevated substrate temperature is needed to increase the surface mobility and diffusion of the condensed atoms. It accelerates the chemical reactions which have to take place in the course of the cathode formation. In addition the unwanted condensation of Cesium and Potassium on the walls of the envelope is reduced. The envelope heating system consists of a spiral shape heating element (see Figure 6) which provides a heating power of up to 1 kW. It is surrounded by a stainless steel shield in order to concentrate the heat radiation onto the glass envelope inside the spiral and to minimise outgasing due to warming up the rest of the equipment.

Figure 6 show also the two light beams which are used to monitor the thickness of the Antimony layer and the quantum efficiency of the photocathode. In Figure 7 the optical system is shown which supplies the two different light sources.

The thickness monitoring is achieved by measuring the light absorption of a LASER beam at 632 nm (HeNe LASER). The attenuated LASER beam is reflected from a small mirror mounted close to the evaporation source. It therefore passes twice through the Antimony layer before it is detected with a silicon photodiode.

The quantum efficiency is monitored by a direct measurement of the photocurrent between the photocathode and and the metallic cylindrical diaphragm which surrounds the evaporation source. The diaphragm is electrically insulated from the support plate which carries the evaporation source. A voltage of the order of 100 V is applied to efficiently collect the emitted photoelectrons. The peak quantum efficiency of K_2SbCs is expected at about 400 nm. Starting from the white spectrum of a quartz tungsten halogen lamp, this wavelength is selected by an interference filter with ±10 nm bandwidth. To discriminate against noise and a possible contribution from other heat and light sources, the light beam

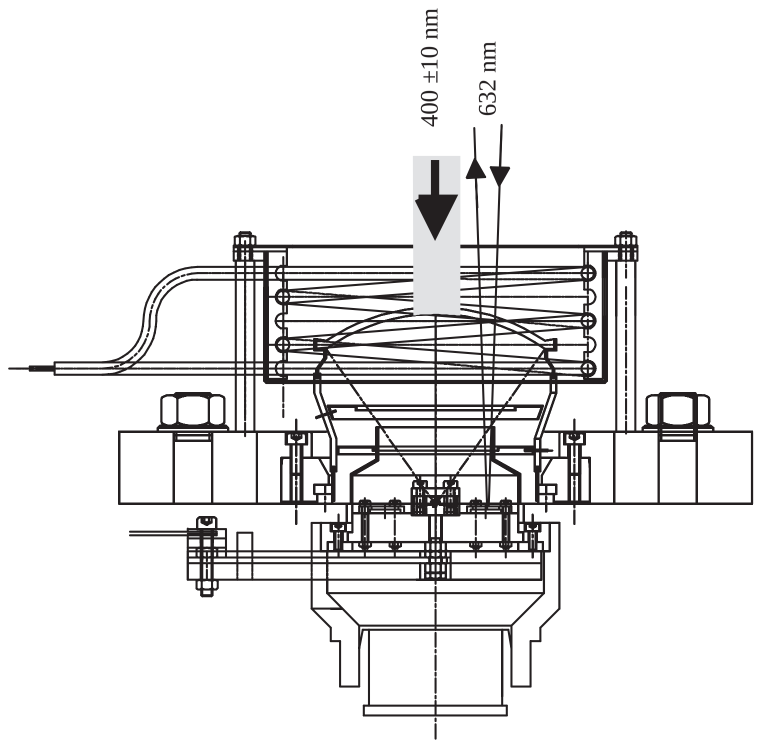

Figure 6: Detailed view of the HPD envelope during the evaporation process. The envelope is surrounded by the heating element. The evaporation source is positioned in the centre of curvature of the HPD window.

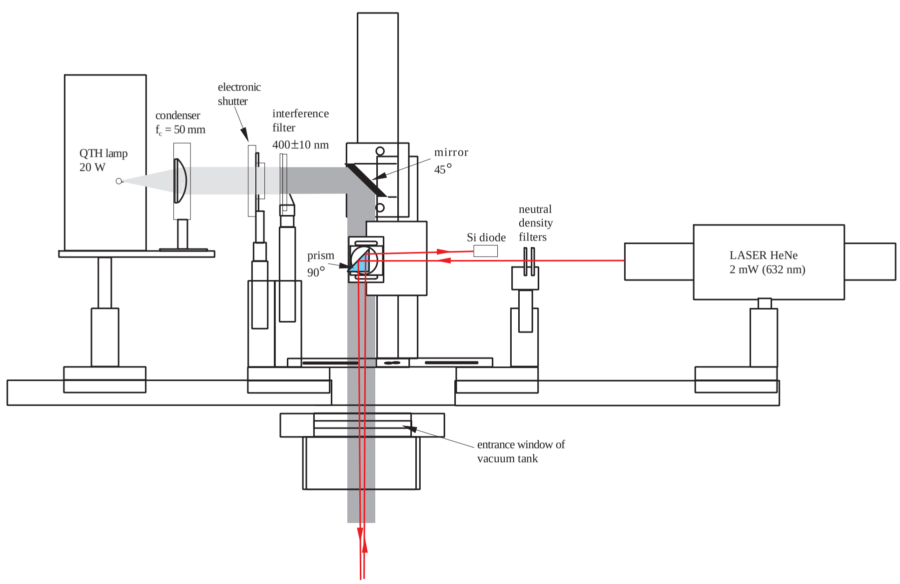

Figure 7: Optical system for the monitoring of the evaporation process.

is modulated by an electronic shutter. For a quantum efficiency of 25 % a photo current of about 9μA is expected.

4 Current status (January 1998)

- The laboratory is fully equipped. Access to the room is still through a normal door. Once necessary, this door will be closed and sealed so that the room can only be entered via an airlock.

- The final assembly of the deposition plant has been performed by an UHV trained technician under optimum conditions (in a tent under laminar air flow). A Helium leak test at ambient temperature and at a pressure of $3 \cdot 10^{-6}$ Pa did not reveal any detectable signal. The leak tester had a sensitivity of $3 \cdot 10^{-9}$ Pa·l·s^{-1}.

- After mounting the heating jacket, which is powered by 9 individually regulated supplies, the plant was baked out for one week at $250°C$. The Titanium ion pump was baked out at $300°C$. The final vacuum which was reached after cooling the plant down to ambient temperature was $1.7 \cdot 10^{-7}$ Pa. For further bake-outs we expect a reduced bake-out time and a final vacuum below $1 \cdot 10^{-7}$ Pa.

- In tests after the bake-out cycle a problem concerning the function of the central piston was discovered. The necessary play between the piston and its guides had been underestimated so that the piston could only be moved under high friction. The problem was solved by increasing the play and by installing an extra guide directly under the support plate which carries the vacuum envelope.

- All electrical connections inside the vacuum tank (evaporation sources, envelope heating element, photocurrent) are done and tested. The optical system for the Sb film thickness and quantum efficiency monitoring has been assembled. A slow control system, based on the fieldbus concept (National Instruments, Fieldpoint) has been designed and ordered. In the beginning the system will be used to monitor all essential process parameters. For a later stage we plan to partly automate the operation of the plant, in order to achieve the best reproducibility of the results.

- Various test concerning the Indium sealing technique have been performed. For this purpose a mechanical device has been built, which can be connected to a pumping system and which allows to seal a vacuum envelope with a base plate by exactly the same method as in the deposition apparatus. The best results have been obtained by electroplating both the groove and knife edge surfaces with thin layers of Nickel and Indium, in order to improve the wetablity of the surfaces. A joint has been formed by compressing an Indium wire between the two surfaces. A He leak test with the above mentioned sensitivity indicates excellent tightness. A pressure increase test, performed over one week, indicates an air leak rate below 10^{-14} Pa·l·s^{-1}.

- All essential components and sub-systems of the deposition plant are now available and to a large extent commissioned. First evaporations can be envisaged in the near furture.

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