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DELIVERABLE REPORT

RESULTS FOR GaAs PHOTOCATHODES

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Abstract:

HZDR plans to apply bulk GaAs photocathode in SRF gun for high current electron source. Supported by this project, a preparation system for GaAs photocathode has been developed. The cathode plugs special for GaAs wafer have been modified and proofed in SRF gun real running conditions. Virgin GaAs wafer was tested in the SRF gun cavity, and the first GaAs activation was performed.

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Delivery Slip

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TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

The SRF gun with Cs_2Te photocathode and UV laser has been developed and operated at HZDR. For the higher average current source, a cathode with higher quantum efficiency (QE) is needed, for example, NEA-GaAs(Cs, O) has good QE in the visible light range.

HZDR has performed the tests on bulk GaAs wafer cleanroom wet treatment and the vacuum heating cleaning. SEM/EDX was used to analyse the fresh surface after the etching process. The inactivated GaAs was installed into the SRF gun cavity, and the dark current /field emission, rf power loss on crystal were measured. The positive results give us more confidence about the application of GaAs photocathode inside the superconducting cavity. The cathode plugs to hold GaAs wafer have been designed, modified and proofed in clean room and in SRF gun, and the transportation for the plugs has been designed.

A test chamber was built for the wafer activation test. Because the vacuum was not sufficient for GaAs cathode, the first GaAs activation failed. Later GaN(Cs) cathodes were successfully activated in this test chamber. The new preparation chamber with extreme high vacuum ($1x10^{-11}$ mbar) has been designed and built at HZDR, and the assembly and commissionning are intensively going on. At the moment the GaAs photocathode with high quantum efficiency has not successfully achieved, but with this fine designed new chamber and the experience gained during the EuCARD project, the research programme has been confirmed by the Helmholtz society, and the preparation of high QE GaAs photocathode is expected in the next months.

2. INTRODUCTION

Although Cs_2Te semiconductor is a suitable photocathode for SRF gun at HZDR, its requirement on the UV laser is critical. The GaAs photo cathode is interesting for the development of SRF photo gun, because it shows high quantum efficiency (QE) in the visible light range, instead of Cs_2Te photocathode driven by UV light. The efficiency of UV conversion (in BBO crystal) from green light to UV light is very low, typical less than 25%. And also the UV laser profile shaping is more complicated than in the case of longer wavelength laser. GaAs material requires only green to blue drive laser, which saves laser power and then the cost on the laser building. If the bunch charge higher than 1 nC with special bunch shape is required in the future, the present Cs_2Te photocathodes and the UV laser system will face an extremely big challenge. Based on this background, the alternative photocathode for the SRF gun, NEA-GaAs is under developing at HZDR supported by this project.

The III-V semiconductor, NEA-GaAs, is up to now the best choice for the polarized photocathode material and the common photocathode for the high average electron sources of ERL or FEL facilities. Negative electron affinity (NEA) is a state of a semiconductor surface where the vacuum energy level E_{vac} is lower than the position of the bulk conduction band minimum E_{CB} [1]. For the GaAs cathode, this NEA can be obtained by covering the clean surface of a heavily p-doped semiconductor with small amounts of Cs and O or F, so called activation. In this case, electrons in the conduction band can leave the crystal surface very easily to vacuum, and thus the high QE can be achieved. The quantum efficiency is an important parameter for photocathodes, defined as the ratio of the number of photo-electrons over the number of illuminating photons.

$$Q.E. = \frac{N_{electrons}}{N_{photos}} = \frac{I_{electron}}{e}\frac{h\nu}{P_{light}}$$

The QE of semiconductor photocathodes is normally 1~10%, and that of metal photocathode is 10^{-6} ~10^{-4}.

In the R&D of GaAs photocathode, we focused basically on three points: the GaAs wafer treatment, the new preparation chamber and the GaAs activation process.

3. MODIFED CATHODES AND TESTS

3.1. TESTS OF GAAS WAFER TREATMENT

The commercial 0.36 mm bulk p-type GaAs (Zn doped 9×10^{18} cm^{-3}) semiconductor is chosen as our first test sample (wafer Technology LTD. from U.K.). The 2-inch wafer is then cut in the clean room to 5mmx5mm pieces for the treatment tests. We use the published acid etching process [1] to clean up the wafer surface. The process is as following:

1. Ultrasonically clean beakers, Teflon tweezers, sample-box and cylinder in acetone and methanol, then blown with dry N_2.
2. Mix 4:1:1 of concentrated H_2SO_4, 30% H_2O_2 and H_2O by volume.
3. Ultrasonically clean wafer at low power in methanol for 3 min. Decant methanol and repeat once.
4. Blow dry with filtered dry N_2
5. Etch in 4:1:1 acid solution (from step 2) at room temperature for 3 min, side faced.
6. Rinse in 10 charges of deionized water and 6 times with methanol.
7. Blow dry with filtered dry N_2.
8. Put into the clean sample-box, and sealed in N_2 bag.

The etched thickness is assumed as about 10 µm. After this process, scanning electron microscopy/energy dispersive X-ray analysis (SEM/EDX) was used to analysis the surface morphology of GaAs samples (SEM Zeiss EVO 50/ EDX: Bruker AXS QUANTAX 200). Figure 1 shows the SEM photo of the etched sample and the EDX spectra of the same sample. The element contents can be calculated from the EDX spectra. From the SEM photo, optical mirror like surface of the etched sample is homogenous and shows good crystal quality. From the EDX measurement, one can find that the O content on the surface is reduced by the etching process. The decrease of the Ga/As ratio indicates that the top layer consists of As atoms.

Figure 1: SEM/EDX measurement after the etching process. The table shows the compare of the EDX measurements of the original wafer and the etched sample.

3.2. INACTIVATED GAAS TEST IN SRF GUN

An inactivated GaAs wafer has been transferred in to SRF gun and been tested with RF field. This sample was 5mmx5mm, but covered with Ø 4 mm Copper disk (figure 2). The goals were to measure the dark current (field emission) from GaAs and the dielectric RF loss in GaAs wafer.

Figure 3 shows the dark current measurement results, and compares different cathode materials in gun. The dark current was measured with Faraday cup, 1 m downstream far away from the cathode. With the increasing RF field, the field emission rises, following the Fowler-Nordheim equation [2]. The field amplitude on cathode surface position is 60% of the maximum axis field shown in the diagram. The black-stars show the dark current of the cavity without cathode inside. This measurement is possible with Rossendorf SRF gun, because the RF filter behind the half cell cavity ensures the rf resonant with empty cathode hole on the back side, and the resonant frequency is of course changed and the cavity must be tuned back to 1.3GHz. The blue triangles are the dark current of the cavity with Cs_2Te photocathode layer. The cesium in the photoemission layer is believed to contribute about 30% of the total dark current [2]. The red points present the dark current of the cavity with inactivated GaAs crystal, which are equal to the black stars value, the niobium cavity without cathode plug. From the diagram, the field emission from GaAs wafer was not found up to 14.5 MV/m (9MV/m on cathode).

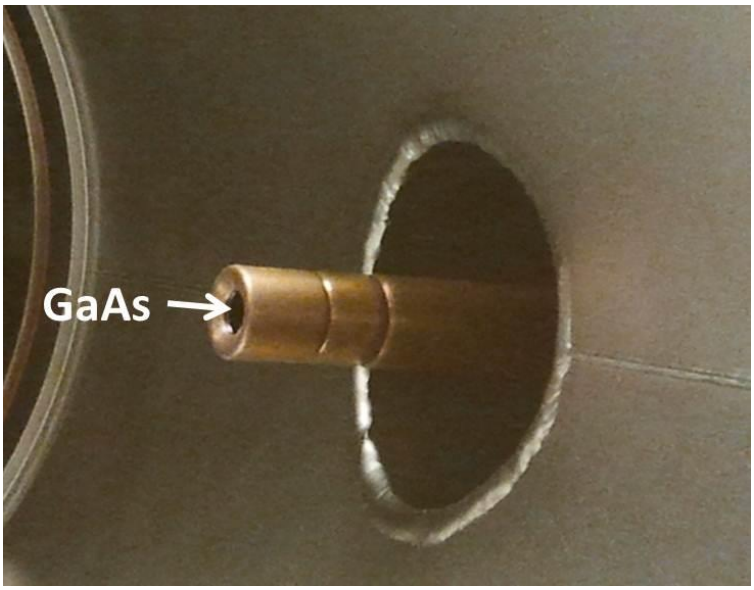


Figure 2 The GaAs wafer held in cathode plug.

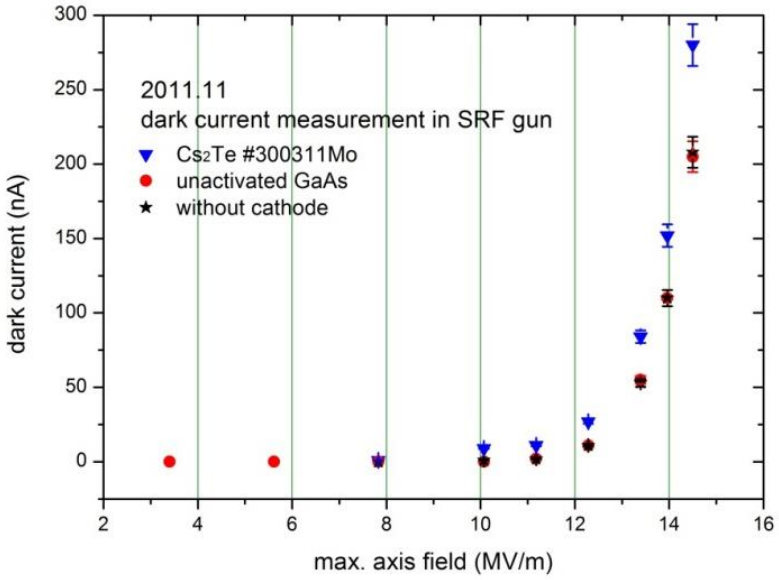


Figure 3: Dark current measurement for SRF gun with different cathode materials.

We must consider the resistant loss and the dielectric power loss when GaAs is put in RF field [3]. The dielectric rf power loss can be calculated with equation $P = E^2 \omega A d \varepsilon_r \varepsilon_0 \cdot tg\delta$,E is the electric field penetrated into the crystal, ω is the rf frequency, A surface area, $\varepsilon_{r,GaAs} = 12.74@75.6K$, ε0= 8.85×10^{12} Fm^{-1}, $tg\delta_{GaAs} = 0.0004$. This power loss on cathode will not affect the superconducting cavity, because the cathode is isolated with cavity and cooled extra with liquid Nitrogen (figure 3), which cools also the nitrogen shield of the gun cryostat and the rf power couplers. Figure 4 shows the nitrogen log during the experiment with GaAs. The gas flow meter logged down the nitrogen flow, and the difference between the data with RF field and the ones without RF field gives the information of the rf field power lost in the coupler and in cathode. In the case without RF, the power to N2 is the static thermal leak from the surrounding. From the linear fittings, this is only 0.12 Liter/min more gas flow through. For N2, its boiling point is 77.36K, and gas density 1.185 kg/m^3 @ 15^{o}C, heat of evaporation is 5.56 kJ/mol or 198.38 kJ/kg. Thus, each liter N2 through Gas flow meter is 1.185 g, which needs the latent heat of evaporation of 235.08 Joule. Or, dQ/dV= 235.08 J/liter. Here Q is the heat of evaporation; V is volume. 0.12 L/min gives the power to N_2

$$P = \left(\frac{dQ}{dV}\right) \times \left(\frac{dV}{dt}\right) = 470mW$$

including the power lost in coupler and also in cathode. So the power loss caused by the GaAs cathode is very little and the effect to the SC cavity can be ignored.

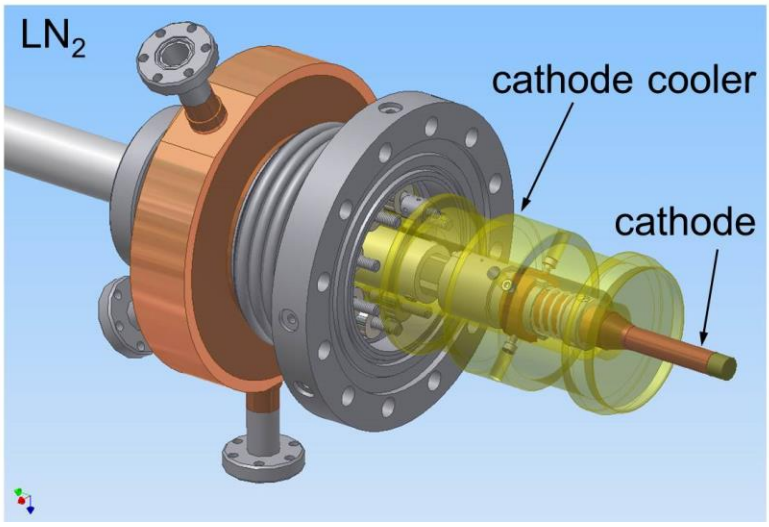


Figure 4: cathode cooling body. Cathode is kept at 77 K with liquid nitrogen.

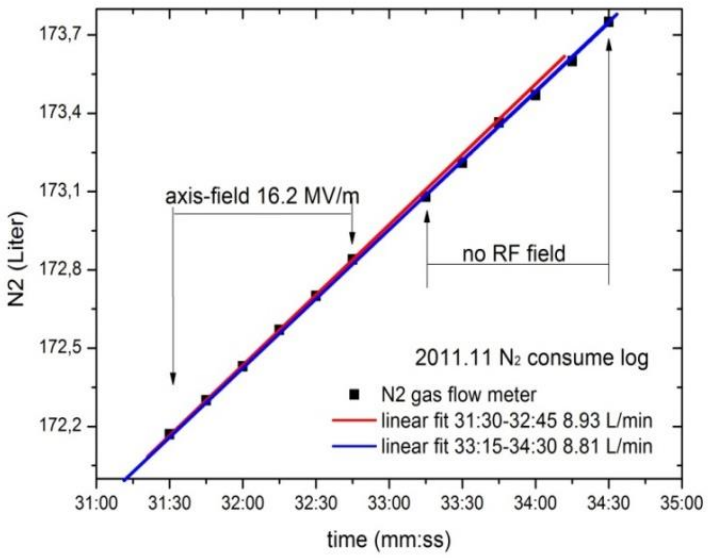


Figure 5: the nitrogen log during the experiment with GaAs. The gas flow meter logged down the nitrogen flow, and the difference between the data with RF field and the ones without RF field gives the information of the rf field power lost in couple and in cathode.

3.3. DESIGN OF A GaAs CATHODE PLUG

The cathode tip into SRF gun is with diameter 10 mm, but the total cathode body is 106 mm long because of the mechanism for the fixing and the thermal contact to LN_2 cooling body (figure 6(a)). We must figure out how to attach the GaAs wafer on the top of plug. First of all, wafer must be covered without naked edge in rf field. Reference [4] shows that the edge will contribute more power loss. Secondly, if the cover shapes a pierce cone, it will help to modify the beam dynamics with higher bunch charge.

The first version is as shown in figure 6(b) and figure 7. The cover is made of copper with pierce cone shape, GaAs wafer is in the cover with 4mm diameter exposed to rf field. A sheet of Indium is used to glue the wafer on the copper base, which provides good thermal contact

and conductivity for wafer. Then the plug is installed onto cathode body through the thread. This version has been tested in SRF gun and the principle is proofed.

Figure 6: photocathode plugs for SRF gun. a: for Cs_2Te; b: 1st version for GaAs.

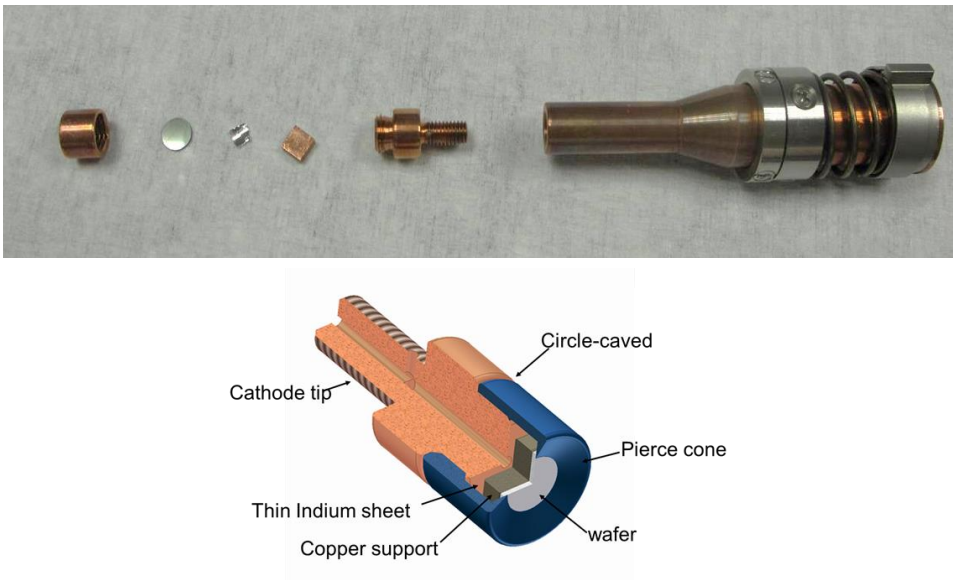


Figure 7: the 1st version of GaAs cathode plug.

However, this design faced a challenge: how to transport the sensitive GaAs cathodes? Another approach was to minimize the plug size and transport only the small tip. In this way, a small transport chamber can be built with reduced vacuum volume. Under this approach, we designed the second version as figure 8. The small tip (also called puck) (Ø 10mm x 6mm) is made of molybdenum with pierce like shape. GaAs wafer is covered inside of the puck, indium glued on a copper nut, which is screwed in the puck. A beryllium spring is used to connect the cathode body and this puck. Spring can provide an easy way to mount and discharge puck from the cathode body by using a manipulator.

The second design has been tested in SRF gun, but only the Mo puck without GaAs wafer inside. We have not found mechanical, electric or thermal problem for this design at the moment.

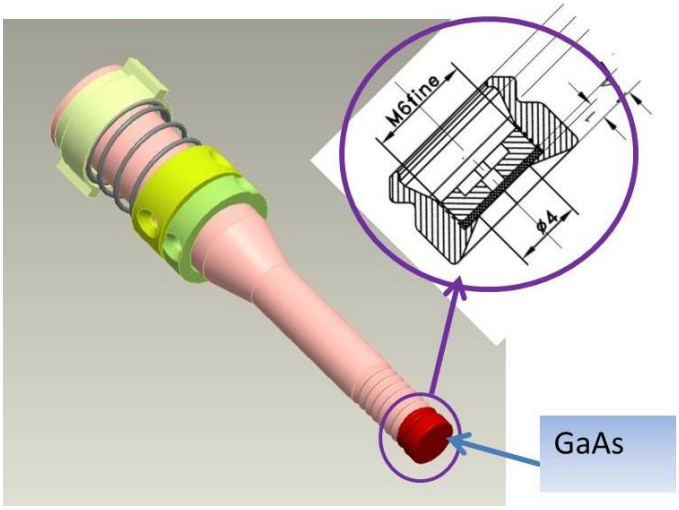


Figure 8: the new design of GaAs cathode plug made of Mo (puck).

A manipulator can hold the puck (figure 9 a), dismount it from the transportation Mo plate (fig. 19b, 18mmx18mmx1mm) and then fix it on the cathode body. This Mo plate is used to transport the pucks and to fix the puck in preparation chamber. The transport chamber and the carrier (fig. 19c) are under construction.

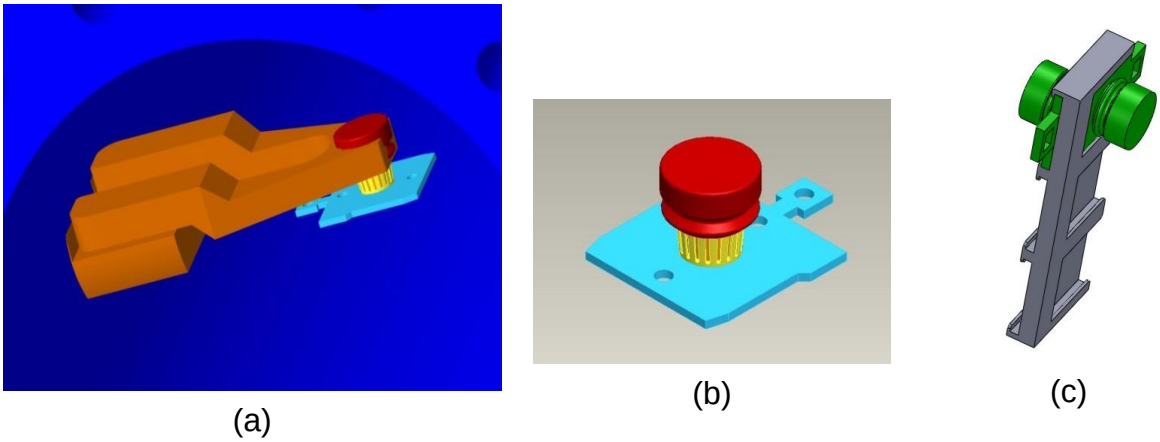


Figure 9: the puck handling in vacuum; the plate and the carrier used to transport the pucks.

Only the small puck is transported and deposited in the preparation chamber. We made the tests for the mechanical behaviour and the particle generation in the cleanroom and in the present photocathode transportation system. Figure 10 shows the particles generated during one puck exchanging. The puck was pulled away from the spring and then pushed on the spring again. All particles have been counted by the clean room particle counter. The particle size smaller than 1 μm is the main source from the result and several tens particles are the normal case. In view of vacuum technology, this result can be acceptable in the transfer chamber, and also safe for the superconducting cavity since the exchange happens in transfer system, which is far away from it.

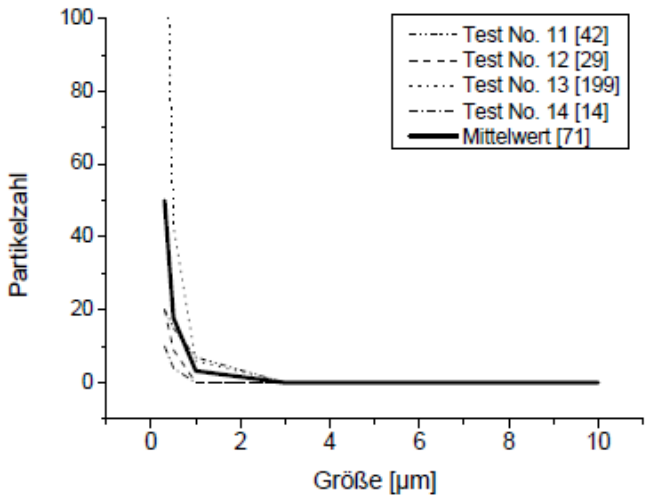


Figure 10: Particles generated during one cathode exchanging with the new designed cathode plug

4. DESIGN AND CONSTRUCTION OF GaAs CHAMBERS

4.1. PREPARATION CHAMBER I

For GaAs cathode, we built at first a small test chamber (figure 11). An electric polished double cross was used as the vacuum chamber. With ion getter pump the final vacuum reached $1x10^{-9}$ mbar. The GaAs wafer was fixed on a tungsten heating bed, and diagnostic light was coupled onto the wafer through a quartz window. SAES Cesium dispenser was installed in front of wafer surface, O_2 was through a needle valve (figure 12).

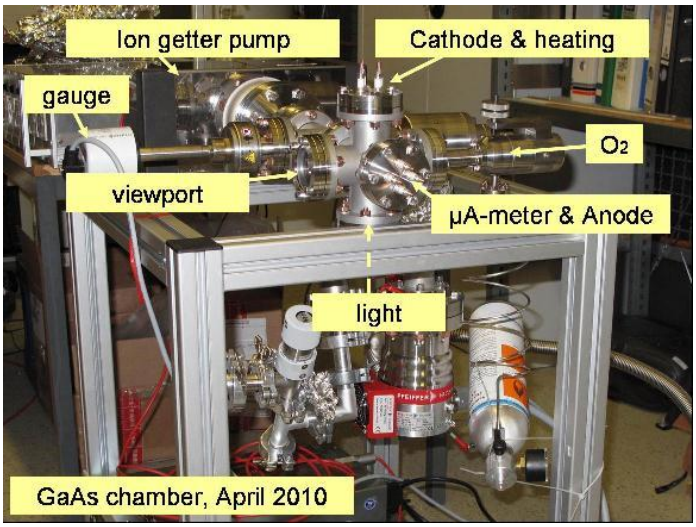


Figure 11: small test chamber for GaAs photocathode.

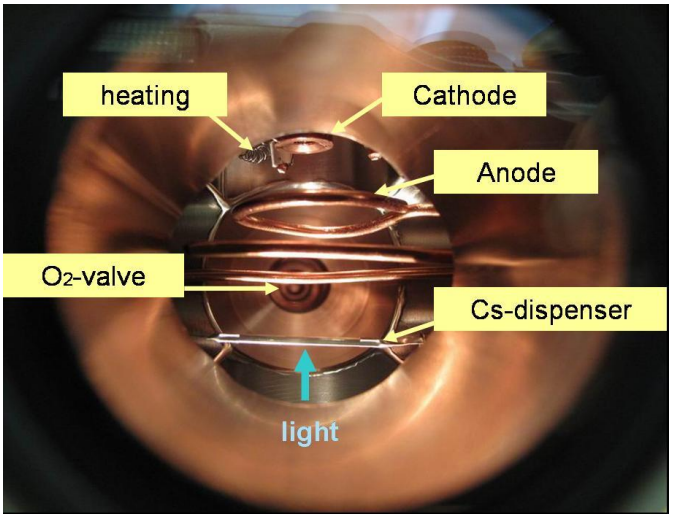


Figure 12: the inside view of the small test chamber.

In this small chamber, we have done the heating treatment test and the first activation test (see section 5.1). However, because the vacuum was not good enough for GaAs photocathode, we developed another preparation chamber system.

4.2. PREPARATION CHAMBER II

From 2012 on we started to design and build a sphere chamber with bigger ion getter pump and SAES NEG pumps. The design goal is to reach $1x10^{-11}$ mbar and with load-lock system for the new sample installing. Figure 13 shows the vacuum design of the preparation system, together with load-lock system and transport chamber. The vacuum pumps are selected as following: For the Ø 300 mm sphere chamber, the volume of the main chamber (no ports in calculation) is 14 liter, and the surface area is 2826 cm^2. Considering the roughness of the E-polished surface and the tubes, attachments, the total surface area is estimated as three times that of sphere surface $A \approx 2826x3 \approx 8500cm^2$. The pressure of vacuum volume can be calculated by

$$P=Q\times A/s$$

here

P: pressure (mbar), Q: outgassing rate (mbar•l/s•cm^2), A: area (cm^2), S: pumping speed (l/s)

Outgassing rate of the metal surface depends on the baking temperature and the pumping duration. According to the reference http://vacuumtunes.co.uk/vtut1.html , if 250 ^oC is chosen for the standard baking temperature, after 100 hours baking, the outgassing rate will be $Q=2.8x10^{-12}$ torr•l/s•cm^2.

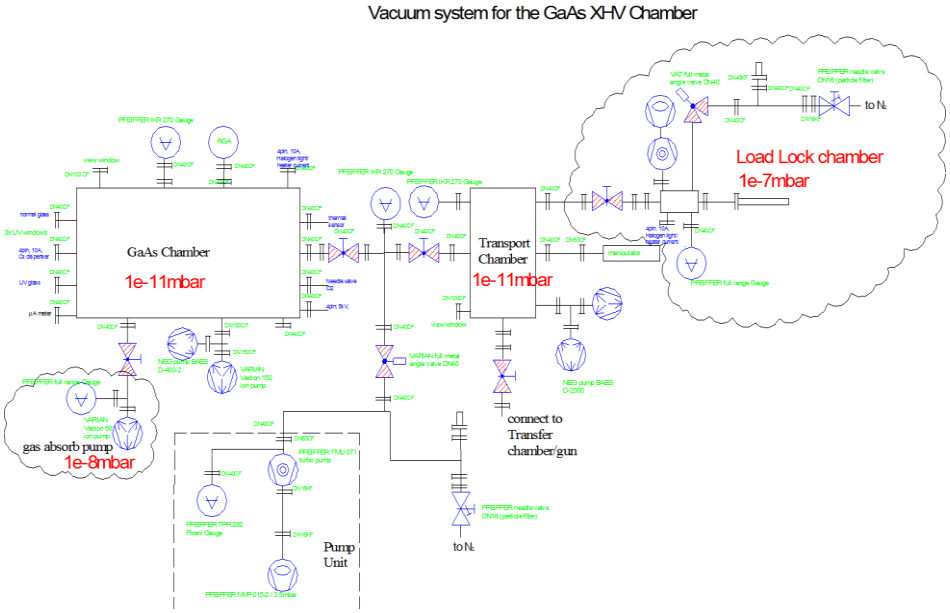


Figure 13: Drawing of vacuum design of the GaAs preparation system.

Outgassing rates in Torr l/s cm2

BAKING TIME				
BAKING TEMP	20 hrs	40 hrs	100 hrs	200hrs
150C	6.3E-11	5.3E-11	2.8E-11	2.0E-11
250C	6.3E-12	5.3E-12	2.8E-12	2.0E-12
400C	4.0E-13	1.7E-13	1.0E-13	1.0E-13
500C	8.0E-15	8.0E-16	4.0E-17	8.0E-19

http://vacuumtunes.co.uk/vtut1.html

Table 1: Outgasing rates

For GaAs photocathode activation, the vacuum of $1x10^{-11}$ mbar is expected, so the required pumping speed can be calculated as S=2380 l/s.

In order to reach this pumping speed, we choose SAES NEG strips (WP1250 St707 alloy) inside vacuum chamber for the maximum pump speed [5]. Each module can provide pump speed up to 560 l/s for H_2 and 220 l/s for CO at room temperature. Three NEG strips together with ion getter pump (Varian VacIon Plus 55) should keep the preparation chamber in range of 10^{-11} mbar after baking.

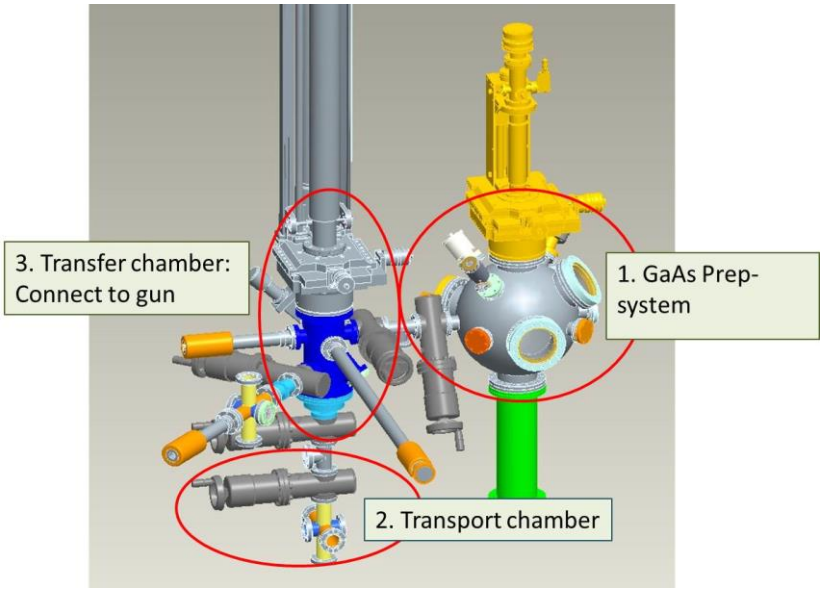


Figure 14: the new GaAs preparation chamber, together with the interface to gun and the transport chamber.

Figure 14 shows the design of new chamber. A Ø 300 mm sphere Non-magnetic SS chamber with electric polished inner wall is used as new preparation chamber. Pfeiffer Trinos delivered this chamber to HZDR (figure 15). The clean room assembly will be done in the next weeks. In figure 14, the transfer chamber works as the interface to connect the preparation chamber with the SRF gun and to insert the cathode into gun cavity. A magnet manipulator pulls the plate with puck (please see back to figure 9 b) from sphere chamber to the "blue" transfer chamber, and then another short manipulator with a jaw described in figure 9a holds the puck and picks it off from the plate spring. At this point, the cathode body is waiting on another long manipulator. The puck is then pushed onto the spring of the cathode body tip. Now this cathode is ready to be inserted into gun cavity by this long manipulator.

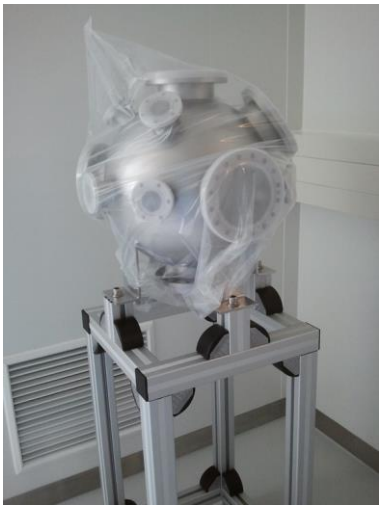


Figure 15: The sphere preparation chamber is waiting for the assembling in the clean room.

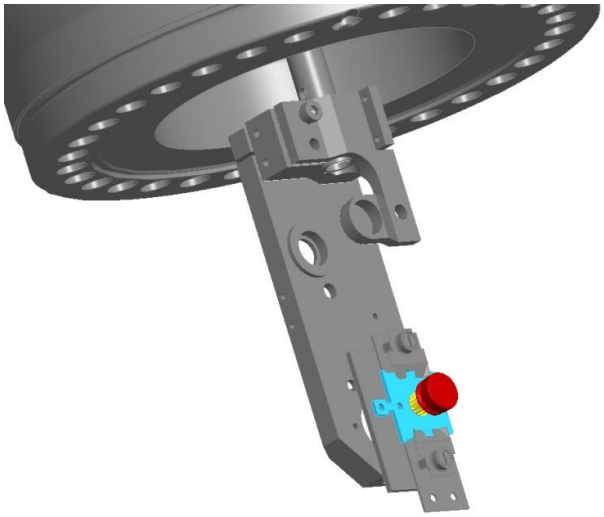
Besides the preparation chamber and the "blue" transfer chamber, there are still two other chambers in figure 14. One is the transport chamber below the blue interface chamber, the other is a small one hanged on blue chamber through an all metal valve. The transport chamber is designed to store up to 4 pucks with GaAs cathodes and to transport the cathodes

to the other photoinjector laboratory or the material analysis facilities. Thus, two all-metal valves are used between the blue chamber and this transport chamber. The small "yellow" chamber is the load-lock system with vacuum of $1x10^{-7}$ mbar (vacuum design Fig. 13), used to load new plate with puck into the XHV system. This loading chamber is not hanged on the preparation chamber, because not all pucks are used for GaAs preparation and unnecessary cesium pollution can happen for the other materials in the preparation chamber.

Ion getter pump stands below the sphere chamber, together with three NEG strip modules will be installed under the sphere (green part for NEG st707 strips, each strip 560 l/s for H_2). For the vacuum measurement, the Leybold IE514 extractor gauge will be installed, which can measure down to $1x10^{-12}$ mbar extremely high vacuum. And the Stanford RGA200 is used for the rest gas analysis in the preparation chamber.

On the top of the sphere GaAs preparation chamber, a complete X-Y-Z-φ bellow stage (figure 16. Vg Scienta [6]) is used to hold the plate with puck and to rotate / adjust the wafer surface position among different stages: halogen light heating, activation, characterization.

(a)



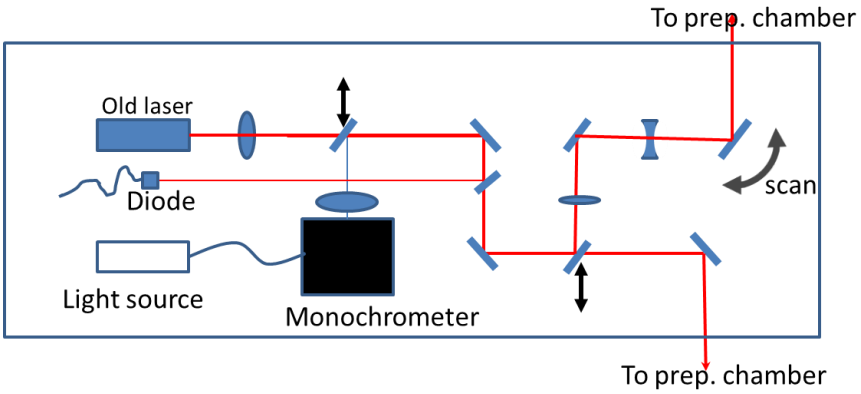
(b)

Figure 16: The main manipulator for the GaAs photocathode handling. (a): the manipulator is waiting for the assembling in the clean room. (b): the view of the cathode holder with the cathode puck on the manipulator.

In our chamber, the activation process will be done with Cesium and O_2. Because we have experience with SAES Cesium dispenser for our Cs_2Te photocathode preparation, the 10mg Cs dispenser is chosen as the cesium source. In order to realize the finest O_2 flow control, we use the computer controlled piezo-electric gas doser PLV1000 from Oxford Applied Research. This all-metal UHV compatible doser can be adjusted in the leak rate level of 10^{-9} mbar·l/s, and the response time can be as short as ms [7].

During the activation and for the characterization, light source with green light is required. We have a UV laser for the Cs_2Te photocathode preparation, and it can be also used for the activation monitoring. Figure 17 shows the layout of the optical beam line and the photo of

the new light source. A green diode laser is placed close to the old UV laser for green light. And on the same optical table, a 20 W Deuterium Halogen light source (Ocean Optics DH-2000, 210 -1700nm) and a monochrometer (SP-2155 Acton Research Spectrapro) are installed to provide the tunable light for the cathode response spectrum measurement.



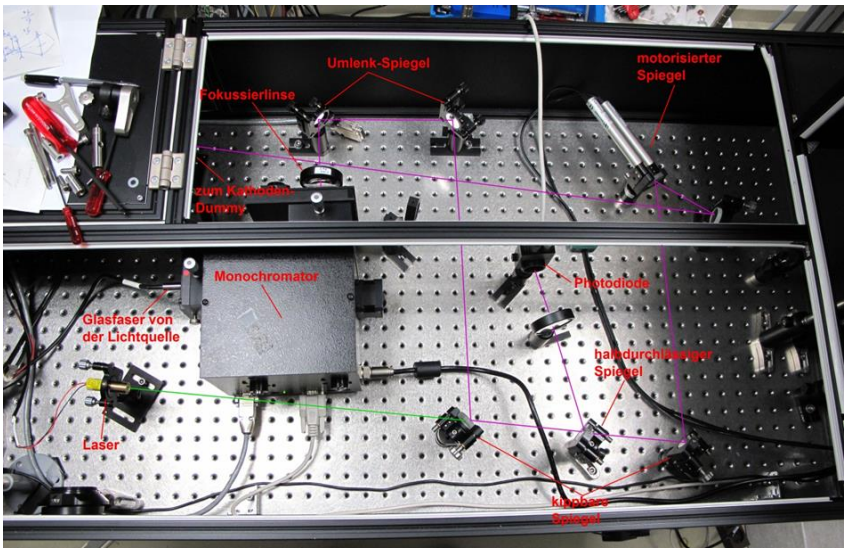
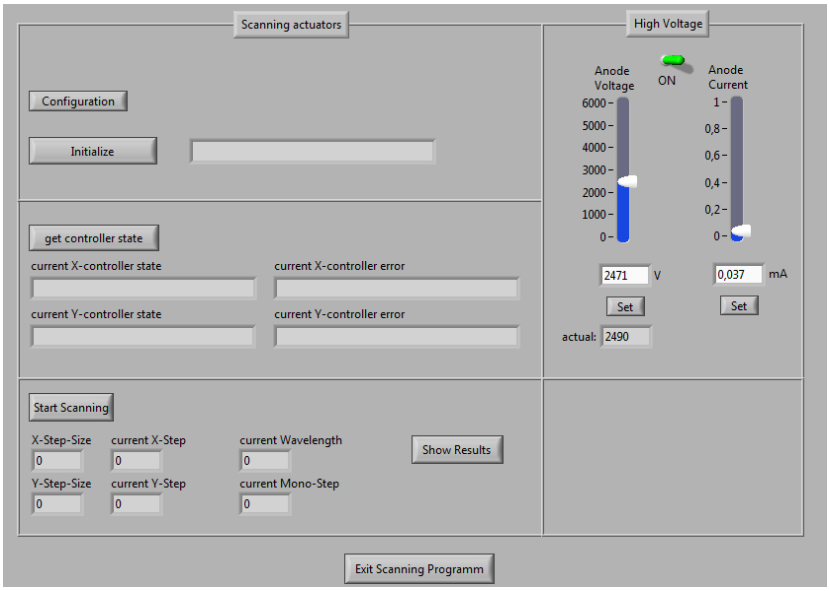


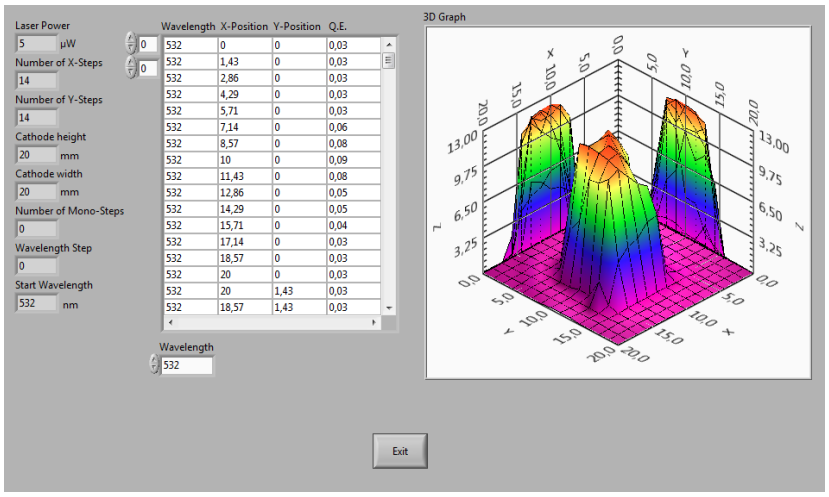
Figure 17: (a) the light source for the GaAs preparation monitor and analysis.

(b) The beam line for the cathode scanning.

The closed loop servomotor from New Focus is chosen as the scanner. Its finest angle step is 0.0005°, which is accurate enough for our cathode scan. A program based on the Labview has been developed for the cathode scanning [8] (figure 18). The scan step size, the light wavelength can be chosen and the anode voltage can be adjusted with the program. Light power and wavelength will be logged down and QE for each step will be calculated and shown in a 3D or 2D distribution map (figure 18.b).



(a)



(b)

Figure 18: (a) the cathode scanning controller (b) the scan test result.

4.3. NEW PHOTOCATHODE LABORATORY

For the new preparation chamber, HZDR has built a clean room with a part area of class 100 as the photocathode laboratory (Figure 19). The old Cs_2Te photocathode preparation system and the new GaAs preparation chamber will be installed in it, which is good for the crucial clean process of GaAs wafer and the later installation into the chamber. We have installed a N_2 filled glove box for the GaAs treatment and installation. Furthermore, because this lab is close to the ELBE accelerator hall, the cathode transportation will be much easier in the future.

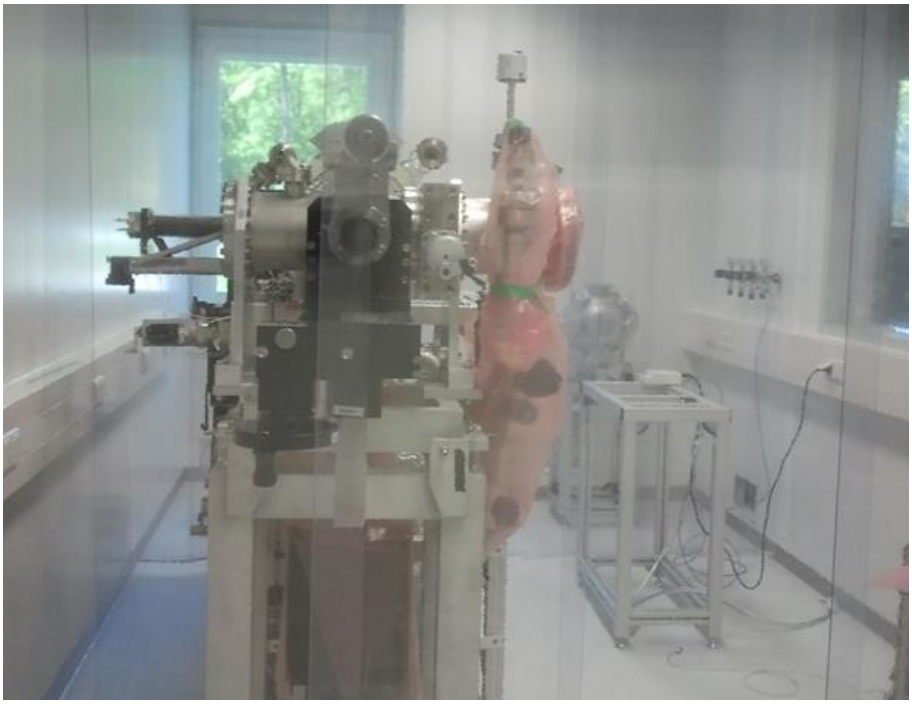


Figure 19: new photocathode laboratory at HZDR.

5. MEASUREMENTS AND RESULTS

5.1. GaAs ACTIVATION TESTS

In the small test chamber (figure 10) we have performed the GaAs activation with cesium and O_2. The electric current through SAES cesium dispenser was 2.5 A, and the UV laser with 0.1 mW average power on GaAs surface. The process was as following:

- Heat wafer with tungsten wires up to about 600^{o}C
- cool down to 100^{o}C
- heat cesium dispenser and monitor the photocurrent
- Open needle valve to O_2
- Stop heating

But there was only nA level photocurrent detected from the cathode during the cesium evaporation, and nearly zero after O_2 was included in the process (fig. 20).

As we mentioned before, the good vacuum is especially important for the GaAs photocathode. However, in the small chamber the vacuum reached only 1x10^{-9} mbar, which could explain the failure of the activation. From this experience, we realized that a new chamber with sufficient vacuum condition is a must for the GaAs photocathode. So during the design and building of the new chamber, we paid extremely much attention on the vacuum issue.

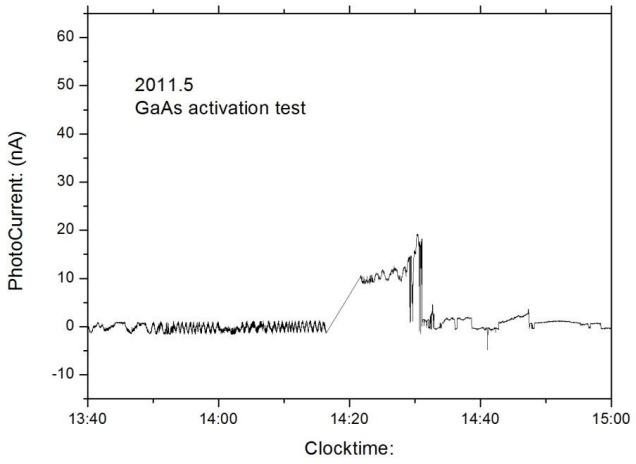


Figure 20: the photocurrent log during the GaAs activation with cesium and O_2.

Because the limitation of the small chamber vacuum cannot be overcome, we changed to use this chamber for negative electron affinity GaN(Cs) tests. GaN is also III-V semiconductor like GaAs. But GaN has brighter band gap (3.4 eV) than GaAs (1.42 eV), so UV laser is required for GaN instead of green light for GaAs. The activation process for both material is similar, but GaN requires only 10^{-9} mbar vacuum, which made it possible to succeed in GaN activation in our test chamber. The following table lists the different characters of these two materials.

Table2: Parameter comparison for GaN and GaAs photocathodes

	NEA-GaN	NEA-GaAs
	III-V semiconductor	III-V semiconductor
E_{gap} :	3.4 eV	1.42 eV
driven by:	UV light	Green, blue light
Activation:	Cs or Cs-O	Cs-O or Cs-NF3
Environment:	10^{-9} mbar	10^{-11} mbar

We tested two samples [9, 10]. The second one was a sample on sapphire with Au/Ni electrode, on which we made the activation tests for 5 times. The typical experiment log is as figure 21(a). Only cesium was used for activation, and photocurrent rose with the cesium deposition. After each activation, a new heating treatment was done, and new cycle activation was made on the fresh surface.

From the experiments with GaN, we learned a lot about the activation process and the diagnostic method, which is useful for the later GaAs photocathodes preparation.

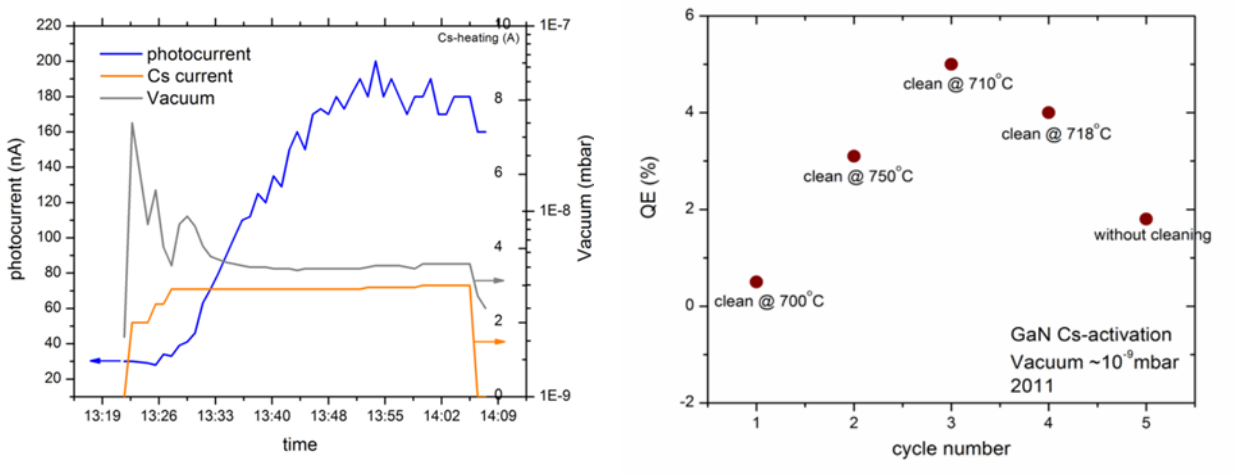


Figure 21: (a) the typical activation process of GaN(Cs)

(b) 5 cycles of activation. The best QE was 5%. [10].

6. CONCLUSION AND FUTURE PLANS

In this report, we present the status of the GaAs photocathode for the SRF gun at HZDR. A special design of a new structure for the cathode plug holding the GaAs wafer has been developed and its mechanical and vacuum properties have been tested. Furthermore, the bulk GaAs wafer has been tested in SRF gun, where no detectable effect to the superconducting cavity could be found. On the other hand, the green light source and the cathode diagnostic system for the new GaAs have been built in our lab. The initial concept for the GaAs cathode preparation system was to combine it with the existing system for Cs_2Te photo cathodes. The reason for that concept was that it would have allowed using the existing mechanical and vacuum equipment for loading the gun with the GaAs cathodes. Furthermore the concept would have been possible with the available manpower and investment resources of the project. The risk was the vacuum. It was known, that GaAs photo cathodes need extreme good vacuum during preparation, storage and transport. Despite some improvements the achieved vacuum was not sufficient and the first activation tests of GaAs photo cathodes were not successful.

Because of this vacuum problem, a new preparation system for GaAs photocathode was developed. This system is a completely new and separate vacuum system with a spherical chamber for GaAs activation in the center. All vacuum chambers, pumps, manipulators are suitable to reach a vacuum of 10^{-11} – 10^{-12} mbar. All parts have already been checked in the new clean room and are waiting to be connected to the sphere preparation chamber. The vacuum processing is expected to be finished before the end of 2013. Following this, the activation will be performed inside the new chamber. With this carefully designed new chamber, we believe the preparation of high quantum efficiency GaAs photocathode will be successful. The cathode transportation system, which will transfer the GaAs(Cs,O) photocathode to SRF gun, is currently under construction [11]. As soon as it is finished, presumably during the next year, the SRF gun will be able to produce electron beam using a NEA-GaAs(Cs,O) photocathode. Initiated by EuCARD the development of the equipment and technology for GaAs photo cathodes, the test and use of GaAs photocathodes in SRF photo guns and their characterization (QE, life time, thermal emittance, field emission) is now an

ongoing research topic within the accelerator research & development programme of the German Helmholtz Society. The sufficient funding by this programme (> 100 kEUR investment per year) allows to continue the work and achieve the objectives in near future

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