Streak Tube Photocathode Development Program

Phase 2 Final Technical Report

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Foreword

The work reported here was supported by the Department of Energy through the University of California, Lawrence Livermore National Laboratory, contract number W-7405-ENG-48 subcontract #B083580. The program was technically directed by R. Lear and R. Haigh.

This report details the progress made toward developing a streak tube with greater than 1% quantum efficiency at a wavelength of 1300 nm. The achieved performance is the result of approximately three years of effort. The work was initially funded via internal Varian R&D funding and then continued under Phase 1 of the the current contract. This work builds upon the previous Transferred-Electron photocathode work performed at Varian in the 1970's under DARPA contract #DAAK02-74-C-0132.

The work was carried out at Varian EO Sensors Division and then after the sale of the division, at Intevac, Electro Optical Sensors Division. Contributions to this work were made at Intevac by V. Aebi, K. Costello, S. Dalton, G. Davis, L. Hobson, R. LaRue, R. Weiss and S. Wright. Contributions to this work were also made at Stanford University by, W. E. Spicer and A. Herrera-Gomez.

Introduction

The goal of Phase 2 of this contract was to seal a working 1.3 μm streak tube. This effort was focused in two areas. First there was a continuing effort to further develop and demonstrate the cathodes ability to meet the stated requirements. The second effort was aimed at solving the mechanical and process related problems related to sealing this cathode onto a EG&G streak tube.

The following section summarizes how the demonstrated tube results stack up against the Phase 1 cathode performance goals.

Quantum Efficiency $\geq 1\%$ @1300 nm / Demonstrated

Electron Emission Impulse Response ≤ 50 ps in vacuum / Demonstrated

Dark Current ≤ 1 micro amp per sqcm. / Demonstrated

Linear Dynamic Range $\geq 400:1$ / Not fully demonstrated

Spatial Active Impulse Resolution ≤ 100 microns FWHM / Steady state resolution has been demonstrated

Minimum active area 20 mm x 1 mm / 18 mm Diameter circular active area has been demonstrated

Lifetime (QE Remains 1% @ 1300 nm)

One year shelf life / Demonstrated

300 hrs power up / Not Demonstrated, no anticipated problems if cathode remains unbiased

5 hrs illumination / Not met by cathode, suggest cathode gating to minimize degradation.

Initial testing in Phase 2 using a higher powered 1.3 μm laser than was available in Phase 1 demonstrated that the 400:1 dynamic range specification was not being met. Therefore, cathode work in the beginning of Phase 2 concentrated on quantifying the process parameters which affect the maximum current density emitted by the cathode. Also at the beginning of Phase two Intevac learned of a similar cathode saturation problem which was being experienced on the GaAs NEA cathodes which are being used in the electron gun at SLAC. As the current densities at which saturation effects set in on the SLAC electron gun were roughly equivalent to those measured on the TE photocathodes at Intevac, we initially feared an unanticipated fundamental current density limit. This led to the issuance of a sub contract to Stanford University to analyze the SLAC data and to determine the mechanism responsible for the current saturation effect and if appropriate to extend the theory to cover TE cathodes.

Results

Cathode development

A review of the current density limits of the tubes built in Phase 1 showed only a limited correlation with the metal overlayer thickness. A second cathode related problem which clearly required attention was that of field emission points. As mentioned in the Phase 1 final report, one potential solution to these problems was the use of a semi-conductor grid. On run number 9-28 the use of heavily doped N-InP grids was attempted. The results were mixed. Although the semiconductor grids appeared to solve the emission point problem and the final etch related undercutting of the grid, these cathodes proved very difficult to manufacture. The lack of a selective etch which could etch through the N-InP layer and stop on the intrinsic InP layer resulted in unacceptably low cathode yields. Similarly, a significant effort was made to develop a metal grid which

would actually melt during the heat clean process. The intent here was to use a grid material which would melt back to the surface and reattach itself, thereby addressing both the emission point problem and that of undercutting during the final etch. However, yield problems were very significant. Therefore, the program focus returned to the use of aluminum grids. However, in an effort to reduce field emission points, the grid deposition process was changed. The initial Aluminum grids were deposited by a multi step process which can be summarized as follows. A negative image of the grid was deposited with photoresist. This structure was then overcoated with Aluminum in a collimated e-beam evaporator. Then the photoresist was dissolved out allowing the aluminum which overlaid it to "lift off" leaving the aluminum grid. This lift off process has the advantage that it is very easy to accomplish at high yield. However, with the current $4 \times 50 \mu\text{m}$ grid geometry, this results in over one million flakes of aluminum which need to successfully float away from each cathode. If part of the flake remains attached, it will likely result in an field emission point in the finished tube. This proved to be a serious problem with this process. In order to address this problem the following process was developed. First an aluminum deposition is done which covers the entire surface of the photocathode. Then a positive image photoresist grid is laid over the aluminum layer. Finally, a selective etch is used which removes the aluminum without significantly etching the InP. This process eliminates the liftoff related field emission points. However the process does not address the issue of undercutting of the grid layer during the final etch. This problem was minimized by shortening the time of the final etch even though this has been shown to adversely affect QE.

Initial cathode development work focused on quantifying the sheet resistance and contact resistance of Palladium on InP. In order to characterize this, a number of test samples were prepared on semi-insulating InP substrates on which resistance could be measured as a function of deposited Pd thickness. Test samples were made with a variety of geometries so that sheet resistance and contact resistance contributions could be separated. The following four graphs review the calculated metal resistivity as a function of metal thickness followed by the measured resistivity and QE vs metal thickness data.

Metal Resistivity Comparison

Figure # 1 Calculated metal resistivity vs thickness.

A comparison of Figures # 1 and 2 show that there is a large difference between the predicted and the measured Pd resistivity. The reason for this discrepancy is not clear. However, any nonidealities in the layer such as surface reactions or microscopic roughness of the surface would tend to increase the resistivity of the layer. Regardless of the cause, the measured data is clearly the appropriate data to use in modeling the anticipated saturation effects on a TE photocathode.

Measured Pd Resistivity vs Thickness

Figure # 2. Measured palladium resistivity vs thickness

Resistance vs Squares

Figure # 3 Measured Pd resistance as a function of geometry.

The data shown in Figure # 3 was taken on two different resistivity samples which contained a series of parallel test pads. The spacing between the series of pads was such that the presented data could be measured. The fact that the intercept of the best fit line through the data points is approximately zero suggests that the contact resistance between the Pd overlayer and the pads is negligible.

Figure # 4 Measured cathode response as a function of palladium overlayer thickness.

Figure # 4 shows the results of an activation experiment in which cathodes were activated to their peak white light photo response (PR) after being coated with various thicknesses of Pd. It was estimated that a white light PR of 220 $\mu\text{A/L}$ was roughly equivalent to 1 % QE at 1300 nm. This estimate is based on an integration of the photon flux between 400-1400 nm from a 2856 K black body source. The approximate color temperature of the light used to perform the activation experiments is 2856 K.

In Figure # 6 of the Phase 1 final report, data was presented showing the response of tube 9C9 as a function of bias voltage. Based on the data, it appears that a voltage drop of approximately 0.8 V would be required in order to drop the QE of the cathode by 10 %. Based on the estimates made in the Phase 1 report, a nominal voltage drop of approximately 0.16 volts could be experienced as a result of the substrate and grid resistance when the maximum optically induced current load of 1

mA over a $100 \times 100 \mu\text{m}$ was applied. This leaves an acceptable voltage drop of $\sim 0.64 \text{ V}$ over the palladium layer. The current grid geometry is a $4 \times 50 \mu\text{m}$ rectangular pattern. A simple numerical model suggests that a voltage drop of 0.64 V will occur in the center of the grid cell at this current density when the sheet resistance of the palladium layer reaches $2.8 \times 10^6 \text{ ohms/sq.}$ Based on Figures # 2 and # 4, this suggests that a usable streak tube should be obtained with Pd thicknesses between 3.5 and $6 \text{ \AA}$.

Based on the metal resistivity results and the activation experiment results, tube # 9A33 was made. This tube used a nominal $6 \text{ \AA}$ thick Pd metalization layer in conjunction with a etched $4 \times 50 \mu\text{m}$ aluminum grid. Before current density began the 7.5 V Schottky barrier bias voltage $1.3 \mu\text{m}$ QE of 9A33 was approximately 0.4% . This is a factor of 2.5 lower than expected. The reason for the low response is not clear. The photo response of the diode dropped significantly during the course of current density testing.

9A33 Current Density

Figure # 5 Tube # 9A33, $1.3 \mu\text{m}$ quantum efficiency as a function of incident $1.3 \mu\text{m}$ light power density.

9A33 PR Loss vs SB Voltage

Figure # 6 Tube # 9A33 % 1.3 μm quantum efficiency loss at 5 W/sqcm as a function of Schottky barrier bias voltage.

Figures # 5 and # 6 show the results of the high light level testing on tube # 9A33. Although the quantum efficiency dropped significantly during testing, the trend toward improved QE retention at higher Schottky barrier bias voltages is clear. The QE loss dropped below the 10 % specification at a bias voltage of 8 V. This is the first time a tube was measured to meet the dynamic range specification up to the testing limit of 5 W/sqcm optical power density. Although this is still below the implied dynamic range specification of 12 W/sqcm, it should be noted that the manner in which the current density test is performed makes this test significantly more demanding than that which is anticipated in an operating streak tube. The test setup is described in detail in the Phase 1 final report. However, to summarize the more demanding aspects of the test, a fiber optic is butted up against the face of the tube. The fiber carries the 1.3 μm light from a laser source. In this case the laser was a 20 mW laser supplied by LLNL. This should induce a current on the order of

15 mA in the Schottky barrier metalization layer at full power as opposed to the expected 1 mA in the streak tube. As such, the voltage drop in the grid and substrate could be on the order of 15 X higher than that assumed in the Phase 1 modeling. This could account for some of the discrepancies between the measured response on 9A33 and that implied by the previously presented data. Similarly, there is no experimental data to quantify the repeatability of the Pd sheet resistance or variances in Pd-grid contact resistance.

A paper written by Verle Aebi detailing some of the results of the cathode development work was presented at the SPIE meeting held in San Diego, California in July of 1993. The paper is included as Appendix B.

Stanford Work

As mentioned in the introduction, Intevac let a subcontract to Stanford University to study charge limit phenomenon being experienced at the Stanford Linear Accelerator Center (SLAC) on their GaAs electron gun. As this was an unanticipated nonlinear affect within a semiconductor photocathode at current densities similar to those required in the streak tube, we felt that it was important to understand the effect. The work was also supported by the Department of Energy through contract # DE-AC03-76SF00515 (SLAC/SSRL), CONACyT-Mexico (AH) and by the dean of engineering, Stanford University (WES).

A. Herrera-Gomez and W. E. Spicer both from Stanford University developed an explanation for the charge limit effect. Apparently, under high current loads the GaAs negative affinity photocathode begins to accumulate charge at the semiconductor surface. At lower light levels, this charge is drained off by a combination of thermionic emission of holes over the band bending related surface barrier and by tunneling currents through the depletion region. This explanation is detailed in the paper titled Physics of High Intensity Nanosecond Electron Source attached as Appendix C. Also included is a Macintosh computer disk which includes the computer model which was used to demonstrate that the proposed explanation could be used to fit the experimental data. In order to further confirm the model, SLAC placed a subcontract with Intevac to seal a number of tubes incorporating Pd coated GaAs photocathodes. The work was done under SLAC purchase order number U. S. 214055-M under contract number DE-AC03-76SF00515. The contract report is included as appendix D. Subsequent, testing of these tubes tended to support the previously described model.

The charge limit model suggests that a continuous distribution of states at the surface of the semiconductor such as that found in a metal will increase the tunneling current on highly doped NEA cathodes to the point where the charge limit effect should be negligible. This was

tentatively confirmed with one of the tubes supplied to SLAC. Within the transferred electron cathode, this surface charge is drawn off through the metalization layer. This leaves the well understood metalization layer resistance issues as the most likely current limiting mechanism for the TE cathode.

Streak Tube Builds

A total of 7 streak tubes were sealed with Transferred Electron photocathodes over the course of this contract. A summary of the exhaust runs performed in support of Phase 2 is attached as appendix A. The text will address the seals in chronological order.

Exhaust run 9-27 contained the first streak tube. The tube was sealed with growth number 40m3064, a 1.4 μm bandgap TE cathode. The cathode was metalized with a 11 $\text{\AA}$ thick silver layer. The cathode activated to a peak PR of 235 $\mu\text{A/L}$ which represents $\sim 1.1\%$ QE @ 1.3 μm . The tube was non-responsive immediately upon removal from the pumps apparently due to a tube leak. Although not definitively found, it appears that the leak resulted from a braze failure between the final ceramic of the Intevac portion of the tube body and the weld flange. Further, analysis showed that the heavy Kovar weld flange placed a great deal of stress on the copper braze material. The stress resulted from the coefficient of expansion mismatch between the AL300 ceramics and the Kovar flange. This resulted in a redesign of the weld flange which broke the unit into two pieces. A thin Kovar member which brazed onto the ceramic and a thicker transition flange to transfer the force from the 1.2 " diameter front end to the streak tube body walls. Measurements on subsequently brazed bodies confirmed that the thin Kovar section takes up the coefficient of expansion mismatch by measurably deforming after braze.

Exhaust run 9-30 sealed the second streak tube which contained the newly designed weld-transition flange combination. The tube was sealed with growth number 40m3224, a 1.4 μm bandgap TE cathode. The cathode was metalized with a 4.6 $\text{\AA}$ thick palladium layer. The cathode activated to a peak PR of 260 $\mu\text{A/L}$ at a 3 V bias. Within two hours after coming off of the pumps the tube was measured to have 1.6 % QE at 1.3 μm with a Schottky barrier bias voltage of 3 V. This QE was essentially unchanged to a power level of at least 0.1 W/sqcm. Unfortunately, this QE dropped by a factor of about a thousand over the weekend before it was delivered to LLNL. Although this in retrospect was almost certainly due to a leak, at this time the conclusion was clouded by the fact that the QE remained relatively stable at this reduced level for a period of weeks. Again in retrospect this could be indicative of a lowered but still measurable escape probability associated with the fully oxidized form of CsO.

Exhaust run 9-32 sealed the third streak tube. The tube was sealed with a 1.4 μm bandgap TE cathode. The cathode was metalized with a 4.6 Å thick palladium layer. The cathode activated to only 120 $\mu\text{A/L}$ but was sealed due to schedule considerations. This tube was dead when it was tested within hours of coming off of the pumps. Subsequent testing wound a large leak in the back end of the streak tube. Apparently this leak opened up during the processing of the streak tube. Surprisingly, no obvious signs of a leak were noted during the run.

Exhaust run 9-34 sealed the fourth streak tube. The tube was sealed with a 1.4 μm bandgap TE cathode. The cathode was metalized with a 5.6 Å thick palladium layer. The cathode activated to only 100 $\mu\text{A/L}$ but was again sealed due to schedule considerations. During the application of the 300 lb press which is used to make the cold indium vacuum seal, an audible popping noise was heard. Again, when the tube was tested shortly after the tube was removed from the pumps the tube was dead. Failure analysis showed the cause of the failure to be cracking which formed in the weld between the transition flange and the streak tube body. LLNL performed a finite element analysis of the stresses on the weld during seal and determined that there should not have been sufficient stress to cause a weld failure. However, it was noted that the transition flange is a very stiff piece of Kovar which is welded directly to the stainless steel dome section of the streak tube. The conjecture is that a weak section of the weld was over stressed by the exhaust bake. Once again a case of a coefficient of expansion mismatch. This once again led to a tentative design change in which the callout of the material of the transition flange material was changed from Kovar to stainless steel. This will place the material mismatch at the thin weld flange / transition flange weld. The intent is to allow the thin Kovar weld flange to deform to take up the coefficient of expansion mismatch. Due to scheduling issues in part related to the EG&G move to LLNL, this fix was never tried. The remaining streak tube seal attempts all used recycled streak tube bodies.

Exhaust run 9-36 contained the fifth streak tube. The tube was sealed with growth number 40m3486, a 1.4 μm bandgap TE cathode. The cathode was metalized with a 4.6 Å thick Pd layer. The cathode activated to a peak PR of 91 $\mu\text{A/L}$. When this tube was taken off of the pumps, it was measured to have a 1.3 μm QE of ~0.16 % at a 5 V Schottky barrier bias. The usefulness of this tube was further compromised by the presence of very high ceramic wall leakage. Approximately 2.5 μA of wall leakage was measured at a cathode to grid bias voltage of 30 V. This may have resulted from the accumulation of cesium on the ceramic walls from this and the previous exhaust cycle. On the next two recycled streak tube seals, an attempt was made to dissolve off the Cs deposited in the previous exhaust cycle.

Exhaust run # 9-37 contained the sixth streak tube start. This tube body was recycled from tube run number 9-30. Although no leaks were definitively found, an inspection of the transition flange to streak tube dome section weld showed a number of voids which may represent pin holes. An attempt was made to seal these voids with limited success with a "solder". The tube was sealed with growth number 40m3486, a 1.4 μm bandgap TE cathode. The cathode was metalized with a 4.6 $\text{\AA}$ thick Pd layer. The cathode activated to a peak PR of 73 $\mu\text{A/L}$. The tube was measured within two hours after it came off of the pumps to have a 0.12 % QE at 1.3 μm . The tube was measured to have a ceramic leakage of 10 nA at 30 V. This is a significant improvement over the previous recycled streak tube. However, this is still orders of magnitude greater than what is normally experienced from a single exhaust processing run. Unfortunately, the QE of the tube dropped over two orders of magnitude over the next two hours, indicating that the leak had not been sealed.

Exhaust run # 9-38 contained the seventh and last streak tube start. This tube body was recycled from tube run number 9-36. The tube was sealed with growth number 40m3562, a 1.4 μm bandgap TE cathode. The cathode was metalized with a 4.6 $\text{\AA}$ thick Pd layer. The cathode activated to a peak PR of 248 $\mu\text{A/L}$ with a modified process. Unfortunately, when the tube was tested, it was clear that there was insufficient contact to the metalization layer to bias up the cathode. Apparently the contact fingers had been bent incorrectly or no longer had enough seating force to perform their function.

In summary, no full spec streak tubes were fabricated. Although 1.3 μm photoemission was demonstrated, time response, and TE cathode life within a streak tube were not characterized. The primary failure mechanism of the streak tubes has been leaks. The design changes mentioned should be sufficient to address the identified causes of the leaks. As a result of the failure of run 9-38, the contact ring was redesigned to incorporate 16 fingers as opposed to the original four. The current drawings are included as Appendix E. The high ceramic leakage on streak tubes 9-36 and 9-37 suggest that even with the cleaning process used on 9-37, recycled streak tube wall leakage may be a problem. Although, there may be a solution to this issue, the only reliable way that we currently have to insure proper isolation is to replace the front end assembly whenever a body is recycled.

Appendix A

Exhaust run table

Exhaust Run Number	Description
9-27	Streak Tube, Dead off pump, probable leak.
9-28	4 TE proximity focused diodes, 2X Ag overlayer, 2X CsO N-InP Grid
9-29	2 TE proximity focused diodes, Pd overlayer
9-30	Streak Tube, 1.6 % QE off pump, slow leak.
9-31	Pd Resistance vs PR experiment
9-32	Streak Tube, Dead off pump, back end leak.
9-33	2 TE proximity focused diodes
9-34	Streak Tube - Large weld leak
9-36	Recycled (9-32) Streak Tube, vacuum tight but high ceramic leakage
9-37	Recycled (9-30) Streak Tube- Soldered weld -slow leak.
9-38	Recycled (9-36) Streak Tube - Cathode contact failure

Appendix B

Photocathode development for a 1300-nm streak tube

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Photocathode development for a 1300-nm streak tube

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ABSTRACT

This paper reports on the status of a program to develop a streak tube compatible photocathode optimized for 1300-nm operation. Performance characteristics will be presented for a Transferred Electron photocathode with greater than 1% quantum efficiency at 1300-nm. Photocathode performance results will also be presented over the 950 - 1700 nm spectral range.

1. INTRODUCTION

Recent results from our program to develop a high sensitivity, high speed, photocathode for 1300 nm operation are presented in this paper. The photocathode is optimized for use in a streak tube. Previous results from this program were presented in an earlier paper¹ where results were presented for Transferred Electron (TE) photocathodes which were sensitive in the 950 - 1400 nm wavelength range. In particular quantum efficiencies as high as 8% at 1000 nm were obtained in sealed tubes. Dark current, dynamic range, emitted electron energy spread, modulation transfer function in a proximity focused diode, and preliminary sealed tube life results were presented. In this paper emphasis is placed on optimized operation at 1300 nm. The device physics of the TE photocathode is briefly reviewed along with its advantages over traditional negative electron affinity (NEA) photocathodes. Experimental results are presented for quantum efficiency, dark current emission, photocathode dynamic range, photocathode time response, and sealed tube life. All of the results presented in this paper were obtained from measurements on sealed tubes. Preliminary results are presented on performance to 1700 nm.

2. TRANSFERRED ELECTRON PHOTOCATHODE DEVICE PHYSICS

The most sensitive photocathodes available today are the NEA III-V semiconductor photocathodes. The basic principle of operation of a transmission mode NEA photocathode is illustrated in Figure 1A.² An incident photon excites an electron from the valence to conduction band of a p-type semiconductor. The photocathode consists of a p-type semiconductor activated with a thin Cs-O layer. The Fermi level is pinned at the surface causing a band bending region to be formed. The p-doping level is typically in the high 10^{18} or low 10^{19} cm⁻³ range so that the resulting depletion region thickness at the surface is 100 Å or less. The bandbending results in the conduction band edge in the bulk of the semiconductor being higher in energy than the vacuum level, ϕ , at the Cs-O surface, hence the term negative electron affinity. As a result, electrons generated by an incident photon with energy greater than the bandgap of the semiconductor have a good probability of being emitted if they are generated within a minority carrier diffusion length of the emission surface. In III-V semiconductors minority carrier diffusion lengths can be as great as 4 μ m in these highly doped materials. Since the optical absorption coefficient is typically high enough that most of the incident light is absorbed over a shorter distance (for light not near the bandedge) high quantum efficiency can be obtained. For transmission mode GaAs photocathodes quantum efficiencies as high as 40% have been measured.³ For similar GaAsP photocathodes quantum efficiencies as high as 60% have been obtained.⁴ The larger bandgap of GaAsP results in more negative electron affinity and thus a higher electron escape probability.

Although these photocathodes have excellent sensitivities, their long wavelength threshold is limited to about 1000-nm by greatly reduced electron surface escape probabilities for semiconductors with bandgaps smaller than ≈ 1.25 eV (wavelengths longer than 1000-nm). The reduced escape probability is primarily a result of an interfacial barrier represented by E_B in Figure 1A.⁵ This barrier height remains approximately constant as the semiconductor bandgap is decreased. The resulting situation is illustrated in Figure 1B. Electrons at the conduction bandedge now must be thermally excited over or tunnel through the interfacial barrier to be emitted into vacuum. This greatly reduces the electron escape probability. At even longer wavelengths the conduction bandedge falls below the vacuum level. When this occurs only hot electrons can be emitted.

In order to overcome these surface barrier effects in long wavelength photocathodes, various externally-biased photocathodes have been studied over the years. Internally biased photocathodes can, in principle, extend the long wavelength cutoff by raising the internally generated photoelectrons in energy allowing emission over the surface work function. A number of p-n junction, MOS, field-emission, and heterojunction bias-assisted photocathodes have been proposed and experimentally studied, but none prior to the development of the TE photocathode⁶ has shown reasonably efficient photoemission combined with the required low dark current emission to be of practical interest.

FIGURE 1A. BANDSTRUCTURE OF NEA PHOTOCATHODE

FIGURE 1B. BANDSTRUCTURE OF LONGWAVELENGTH NEA PHOTOCATHODE

TE photoemission is based on the fact that for certain III-V semiconductors such as InP, InGaAsP alloys, and GaAs, electrons can be promoted to the upper conduction band (L and X) valleys (or simply heat up within the Γ valley) with reasonable efficiency by applying modest electric fields. Photogenerated electrons which successfully transfer to the upper valleys, or become hot Γ electrons are then energetic enough to have a good probability of being emitted over the work function and surface energy barriers into vacuum. Experimental high-performance TE photocathodes for the 1000 to 1650-nm region were extensively investigated at Varian⁷ (and references therein) and more recently at Intevac.¹

A schematic energy band diagram of an unbiased TE photocathode is shown in Figure 2. The active (photon absorbing and electron generating) layer should contain few free electrons in the absence of illumination to minimize dark current generation, thus it should be a p-type semiconductor. The layer which finally emits electrons into vacuum must also have p-type characteristics. In order to apply a bias voltage between the two layers, a "hole barrier" is needed between the two. A hole barrier consisting of a metal/semiconductor Schottky barrier is used for the TE photocathode. The barrier to hole flow for metallic contacts to p-InP is sufficiently high for a satisfactorily low value of hole current, easily sustained by the biasing contact, when the Schottky barrier is reverse biased.

In the structure illustrated in Figure 2 the active photon absorbing layer is a p-type InGaAs layer lattice-matched to InP which is a ternary endpoint of the InGaAsP or InGaAlAs quaternary systems. The InGaAsP quaternary system with the InP lattice constant can generate bandgaps spanning the range from

1.35 eV (InP -- 920-nm) to 0.75 eV ($\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ -- 1650-nm) while the InGaAlAs system with the InP lattice constant can generate bandgaps ranging from 1.47 eV ($\text{In}_{0.52}\text{Al}_{0.48}\text{As}$) to 0.75 eV ($\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$). The electron emission layer is a lightly-doped p-type layer of InP of the order of a micron thick. The Schottky barrier is formed by a ≈ 20 Å thick metallic layer (e.g. Ag) activated with cesium and oxygen to lower the work function of the metal to approximately 1 eV.

FIGURE 2. BANDSTRUCTURE OF AN UNBIASED TE PHOTOCATHODE

Photocathode operation is illustrated in Figure 3. A reverse bias voltage is applied to the metallic Schottky barrier. The photocathode can be illuminated by transmission through the InP substrate (not shown), transparent to radiation at wavelengths beyond 950 nm. The light is absorbed by the lower bandgap optical absorber layer promoting electrons from the valence band to the conduction band where they rapidly thermalize to the Γ conduction band minimum. These electrons are then transported by diffusion into the p-InP Emitter layer which has been depleted by a positive bias applied to the Schottky barrier. The reverse bias establishes a field in the emitter layer greater than 10^4 V/cm. For such fields, which are low compared with breakdown fields (10^5 to 10^6 V/cm), it is known that conduction electrons in InP are promoted in energy near to or actually transfer into upper satellite valleys. The L valleys lie 0.53 eV above the lowest, Γ , conduction band valley. At the surface these valleys are 1.11 eV above the Fermi level of a Ag Schottky barrier which has a barrier height of 0.77 eV on p-type InP. Electrons from the upper valleys of InP can therefore be emitted into vacuum from a Cs-O activated surface. Since promotion to the upper valleys in InP is known from microwave and photoemission work to be an efficient process for fields greater than 1×10^4 V/cm, this configuration makes for efficient transfer of Γ electrons to energies near or at the upper valleys where they can be emitted over the work function barrier into the vacuum.⁷ The applied bias also extends the depletion field back to the absorber-emitter interface, permitting efficient minority carrier electron transport across the p-p heterojunction. The existence of a depletion field also allows the fast time response required by the streak tube application.

Quantum efficiency of the TE photocathode is determined by the internal quantum efficiency defined as the number of electrons reaching the emission surface divided by the number of incident photons and by the hot electron transmission probability through the semitransparent Schottky barrier. Internal quantum efficiencies are quite good with these structures, typically greater than 50%. The primary quantum efficiency limitation is the electron transmission of the thin Schottky barrier. Electron-electron scattering in the metallic film results in energy loss by the photoelectrons reducing their energy below the vacuum level. The electron transmission probability is quickly reduced with increasing film thickness. Electrons not emitted into vacuum are collected by the Schottky barrier. The metallic film needs to have sufficient conductivity to remove this current without an appreciable voltage drop which would debias the photocathode. These two requirements of a thin film for high QE and a thick film for low voltage drop result in an optimum film thickness for a particular illumination level.

FIGURE 3. BANDSTRUCTURE OF A BIASED TE PHOTOCATHODE

The primary sources of dark current in the photocathode are from generation in the small bandgap absorber layer and electron generation due to avalanching in the depletion region initiated by holes injected over the Schottky barrier. The first source of dark current is minimized by using the largest bandgap absorber which is acceptable for the application. For a photocathode optimized for 1300 nm operation a bandgap of 1400 nm is used which minimizes dark current generation while still having a large optical absorption coefficient at 1300 nm. Avalanche electron generation due to hole injection over the Schottky barrier (illustrated in Figure 3) is minimized in the InP system because of the large Schottky barrier height on p-InP. Hole injection is further reduced by using a low p-type doping level in the InP emitter to reduce the peak electric field at the Schottky junction, minimizing tunneling through the barrier.

3. PHOSPHOR DIODE TUBE RESULTS

The majority of the sealed tubes fabricated in this program were 18 mm format, proximity focused, tubes containing a P20 phosphor screen. Results from these tubes are presented in this section.

3.1 Photocathode Fabrication and Structure

A cross section of the photocathode structure used to obtain the results reported in this paper is shown in Figure 4. Photocathode materials growth was conducted in an atmospheric-pressure horizontal organometallic vapor-phase epitaxial (OMVPE) growth system using methyl-based aluminum, gallium, and indium organometallic precursors, arsine and phosphine group V precursors, and diethylzinc and dimethylzinc dopant sources. All growth was performed with (100) oriented ($\pm 0.10^\circ$) InP:Zn substrates having hole concentrations of approximately $1.0 \times 10^{17} \text{ cm}^{-3}$. A low substrate doping level is required to minimize free carrier absorption at wavelengths longer than 950 nm in the substrate. Substrate preparation consisted of degreasing in TCA, acetone, and isopropanol followed by a three minute etch in 4:1:1 $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$.

The typical structure consists of an InP:Zn buffer layer, a $1.0 \mu\text{m}$ thick lattice matched quaternary alloy absorber layer with a bandgap corresponding to 1400 nm, and a $0.10 \mu\text{m}$ thick linear grade to match the conduction band in the absorber and the InP emitter, and a $0.35 - 0.50 \mu\text{m}$ thick InP emitter layer. The majority of the structures and all of the photocathodes incorporating a grading layer utilized the AlGaInAs system. Epitaxial structures exhibit good morphologies and uniform doping and alloy constituent incorporation. Photoluminescence intensities of the full structures are generally two orders of magnitude greater than the intensities of the quaternary epitaxial layers due to carrier confinement by the InP cap layer.

The finished photocathodes had an active diameter of 18 mm. An anti-reflection (AR) coating was applied to the backside of the InP substrate to minimize reflection at 1300 nm. A $12 \times 50 \mu\text{m}$ metal grid was deposited by photolithography techniques on the photocathode. The grid allowed contact to be made to the thin Schottky barrier metallization. Photocathode processing was completed by heat cleaning the photocathode in an ultra high vacuum processing station followed by deposition of the Schottky barrier metallization and activation with cesium and oxygen. After activation the photocathode was sealed onto a proximity focused diode tube to allow photocathode characterization.

FIGURE 4. TE PHOTOCATHODE STRUCTURE

3.2 Photocathode Performance

The measured quantum efficiency of a tube with a photocathode optimized for 1300 nm operation is shown in Figure 5. The quantum efficiency increases rapidly as a function of Schottky barrier bias. This is a result of the better transfer efficiency of the electrons to the L and X conduction valleys at higher bias voltages. Peak quantum efficiency at 1300 nm is greater than 5% for this tube. The photocathode quantum efficiency is very flat versus wavelength as compared to a traditional photocathode. The slight roll off in quantum efficiency at longer wavelengths is due to the reduced optical absorption in the absorber layer with wavelength. This could be improved by increasing the absorber thickness. For the streak tube application this is not acceptable as it would increase the time response of the photocathode.

FIGURE 5. QUANTUM EFFICIENCY AS A FUNCTION OF SCHOTTKY BARRIER BIAS FOR TUBE 9A15

The measured quantum efficiency of several TE photocathode tubes with various absorber layer compositions is shown in Figure 6. An S-1 photocathode quantum efficiency curve is included for comparison. The wavelength sensitivity range of the photocathode can be easily tailored by adjusting the absorber bandgap. The cathodes exhibited good quantum efficiency across the entire band as determined by the bandgap of the absorber layer. Peak quantum efficiencies are in the 8% range. For comparison an S-1, Ag-CsO, cathode has a quantum efficiency at 1060 nm of approximately 0.05% and essentially no sensitivity at wavelengths greater than 1300 nm. Initial results are also shown in Figure 6 for a tube containing a photocathode with an InGaAs absorber layer. This tube was sensitive to 1700 nm. Peak quantum efficiency was low on this tube as it utilized a relatively thick silver layer which reduced the electron escape probability.

FIGURE 6. QUANTUM EFFICIENCY FOR TE PHOTOCATHODE TUBES WITH DIFFERENT ABSORBER LAYER BANDGAPS AS A FUNCTION OF WAVELENGTH COMPARED TO AN S-1 PHOTOCATHODE

The dark current performance of a photocathode optimized for 1300 nm performance is shown in Figure 7 as a function of Schottky barrier bias voltage. The dark current increases rapidly with applied bias suggesting that the primary dark current generation mechanism is impact ionization by holes injected over the Schottky barrier.⁸ By comparison the 1700 nm sensitive tube shown in Figure 6 had a measured dark current of 69 nA/cm² at room temperature for a reverse Schottky barrier bias of 4.5 V. This large increase in emitted dark current is due to increased generation in the small bandgap optical absorber layer.

FIGURE 7. DARK CURRENT AS A FUNCTION OF SCHOTTKY BARRIER BIAS FOR TUBE 9A15 AT 20°C

3.3 Photocathode Dynamic Range

The input power levels required for the streak tube application can be estimated from the required linear dynamic range and with the assumption that the minimum acceptable signal-to-noise power ratio (SNR) is 10:1. The SNR is not dark current limited for an input spot size of 100x100 μm on the photocathode (to allow multi-channel operation of the tube). For signal limited operation the minimum input optical power as a function of snr is given by:

$$P_{\min} = 2h\nu B \frac{F}{QE} \text{snr}$$

where

F = noise factor of tube (assumed = 1)

B = Bandwidth = 10^{10} s^{-1} for 50 ps time resolution.

QE = quantum efficiency (assumed = .01)

$P_{\min}$ is $3 \times 10^{-6} \text{ W}$ for a SNR of 10. For a dynamic range of 400:1 the maximum input power ($P_{\max}$) is 1.2 mW. Under steady state illumination of the photocathode with this power the internally generated current will be 1.0 mA (this assumes 80% optical absorption in a 0.7- μm thick InGaAsP absorber layer, also assuming 100% internal quantum efficiency per absorbed photon). The emitted current from a 100x100 μm spot assuming a 1.25% escape probability into vacuum would be 0.0126 mA. The remaining 0.99 mA must be transported away by the Schottky barrier metallization.

The IR voltage drop across the TE photocathode due to the 1.0 mA of current generated in the structure under maximum illumination conditions can effect the linearity of the photocathode response. A voltage drop across the thin metallization used to form the Schottky barrier or across the p-InP substrate will change the bias across the Schottky diode. A bias change will effect the electron transfer efficiency to the upper level valleys in the InP emitter layer. This in turn will change the quantum efficiency into vacuum of the TE photocathode (Figure 5).

The primary parasitic resistance in the photocathodes fabricated in this program employing the contact grid is a result of the thin metallization used to form the Schottky barrier. Figure 8 shows the dynamic range performance of Tube 9A15 with Schottky barrier bias voltage a parameter. This tube employed a thin metal layer and while it exhibits good quantum efficiency at low light levels a roll off in sensitivity is observed as the light level is increased, indicative of debiasing effects in the photocathode. Figure 9 illustrates the improved dynamic range performance obtained with a thicker metallization layer. Peak quantum efficiency is less as a result of the lower escape probability through the thick metallization.

FIGURE 8. DYNAMIC RANGE OF TUBE 9A15 WITH A THIN METAL LAYER

FIGURE 9. DYNAMIC RANGE OF TUBES 9A30 AND 9A33 WITH A THICK METAL LAYER

Sealed tube life has been good for the phosphor diode tubes built in this program. Figure 10 is an example of the room temperature shelf stability that can be achieved with the TE photocathode. Good stability over periods greater than 2 years have been obtained.

FIGURE 10. SEALED TUBE SHELF LIFE AT ROOM TEMPERATURE

4. TE PHOTOCATHODE TIME RESPONSE

The streak tube application requires a photocathode with a fast time response to allow good time resolution in the streak tube. The TE photocathode is well suited to this application as the internal bias required for photoemission has the additional benefit of rapidly sweeping the carriers out of the photocathode resulting in a much faster time response than that obtained by the diffusion process in a NEA photocathode. For the streak tube application the TE photocathode is designed so that the applied bias can completely deplete both the emitter and absorber layers. For example, with a 0.5 μm thick InGaAs layer, the depletion region for biases in excess of 3 volts would penetrate clear through the InGaAs and terminate in the underlying InP buffer layer (whose thickness and doping would need to be adequate to prevent significant depletion of that layer). The field in the InGaAs is of the order of

10^4 V/cm under these conditions, which would accelerate the photogenerated electrons to saturation velocities in InGaAs -- of the order of 2×10^7 cm/s. The time dispersion of the current pulse injected from the InGaAs into the InP emitter in response to a delta-function input spike of 1300-nm photons can be determined by considering the electron-hole pair generation function, $G(x)$, due to the light absorbed in the InGaAs layer.

$$G(x) = F a \exp(-ax), \quad \text{where } F \text{ is the photon flux}$$

and $a = 1.5\text{-}\mu\text{m}^{-1}$ is the absorption coefficient in InGaAs for 1300-nm photons

The generation rate is seen to fall off exponentially as the light penetrates the InGaAs layer. The carriers generated at $x = 0$ have the maximum distance to travel to the InGaAs/InP heterojunction. The time dispersion of the current pulse emitted from the InGaAs layer into the InP layer is determined by the length of time required for these carriers to reach the InP layer. For the $0.5\text{-}\mu\text{m}$ layer under consideration, with the above saturation velocity, this is 2.5×10^{-12} seconds. The emitted pulse will have a shape given by the above generation function with the current increasing exponentially to a maximum at the end of the pulse at 2.5 ps.

The mean transit time of electrons in this pulse through the grading layer and InP would be determined by the saturation velocity (about 10^7 cm/s) of electrons in the high field in the InP (between 10^4 and 10^5 volts/cm), or about 12×10^{-12} s. Carriers will all be swept out in this time, so that this gives the maximum possible pulse dispersion based on the simplest model -- or 12 picoseconds.

In fact, since longitudinal diffusion of an electron pulse under high field conditions is quite low, the dispersion of the pulse would be less than this. Monte Carlo modeling⁹ shows electron temperatures in the upper valleys to be on the order of 1000°K . Using effective mobilities of $1000\text{ cm}^2/\text{Vs}$, this translates to diffusion coefficients of the order $90\text{ cm}^2/\text{s}$. This in turn gives a spatial dispersion of a delta-function pulse during the 12-ps transit as $0.33\text{ }\mu\text{m}$, or a time dispersion in the emitted pulse of 3.3 ps. Combined with the original InGaAs pulse width of 2.5 ps, this gives a total pulse width into vacuum for an optical delta function input of about 6 ps. The total delay will be of the order of 15 ps.

FIGURE 11. TIME RESPONSE TUBE STRUCTURE

An attempt was made to directly measure the impulse response of the TE photocathode. A high speed anode structure was designed and fabricated. A schematic of the tube configuration is shown in Figure 11. A triode configuration was chosen to remove dependence on the cathode-to-grid gap from the anode structure time response.¹⁰ In this tube configuration the electron acceleration region between the

cathode and grid does not effect the impulse response of the tube for monochromatic electron emission. The tube impulse response is determined by a convolution of the cathode impulse response, the time of flight between the grid and the anode cone and the RC time constant of the anode circuit. The anode capacitance is determined by the grid-to-anode cone capacitance. A $50\ \Omega$ tapered transmission line is used to match the anode to a standard SMA output connector on the tube to allow connection to standard $50\ \Omega$ measurement systems and to minimize any reflections in the transmission line. One modification to the design is incorporation of a Faraday cup in the anode cone. This greatly reduces after pulsing generated by electrons which would be elastically scattered back through the grid by a solid anode cone.

The impulse response of the tube structure in Figure 11 has been modeled assuming monochromatic electron emission and a 4 kV accelerating voltage between the cathode and grid. The result is shown in Figure 12. The rising edge of the response is determined by the transit time of the electrons between the grid and anode cone. The falling edge is given by the RC time constant of the anode circuit. The tube has a fundamental impulse response with a full-width-half-max (fwhm) of 30 ps. The actual TE photocathode electron emission is not monochromatic and has been measured to have a fwhm of 0.6 eV.¹ This results in approximately 7 ps of time dispersion in the electron pulse at the grid after acceleration by 4 kV.

The measured impulse response for a tube containing a 1300 nm sensitive TE photocathode is shown in Figure 13. The fwhm was 50 ps with a 10% to 90% rise time of 35 ps. The optical pulse was generated by a Tektronix OIG502 1300 nm optical pulser. The laser pulse had a fwhm < 35 ps with a peak optical power of 5 mW. The tube signal was measured with a HP 54120T sampling oscilloscope with a 12.4 GHz bandwidth and a 28 ps 10 - 90% transition time. The tube had a 4 kV bias applied between the cathode and grid and a 6 V Schottky barrier bias. The actual photocathode response time is difficult to determine due to the impulse response limitations of the test setup and tube. The measured results are consistent with a photocathode response time of less than 10 ps.

FIGURE 12. MODELED TUBE ANODE IMPULSE RESPONSE

5. CONCLUSION

This work has demonstrated the ability of modern semiconductor, "engineered", photocathodes to be optimized for a given application, in this case for use in a high speed streak tube. It has also demonstrated the viability of the TE photocathode for use in the 950 - 1700 nm wavelength range. Availability of this photocathode is expected to greatly extend the range of usefulness of detectors and imagers which depend upon photocathodes. Future results will report on streak tube results utilizing this photocathode.

FIGURE 13. MEASURED TUBE IMPULSE RESPONSE

6. ACKNOWLEDGMENTS

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Appendix C

Physics of High Intensity Nanosecond Electron Source

Appendix D

SLAC Contract report

Contract Report:

Intevac sales order number: 20396

Customer P. O. No. U. S. 214055-M

Contract No. DE-AC03-76SF00515

Line Item A: Photoresponse vs Pd layer thickness

Three cathodes were etched and loaded into a UHV exhaust station per standard, Intevac proprietary, procedures. The cathodes were then sequentially; heat cleaned, metalized with a measured Pd layer and then activated with Cs and O₂. An attempt was made to mask a portion of the photocathode during the Pd deposition. Pd thickness was monitored via a quartz crystal thickness monitor. Due to the geometry of the station and the resolution of the thickness monitor the minimum discernable thickness increment was 2.8 Å. Hence the error bars with respect to thickness are quite large. A total of 5 photoresponse values including one which represents an uncoated GaAs surface were measured. The non-Pd coated data point is not included in the best fit line. The reported photoresponse values reflect the highest sensitivity reached at the end of a Cs + O codeposition. The light source used to monitor the photocathode was a chopped ~ 2856 K quartz halogen lamp. A lock in amplifier was used to minimize the effects of stray light. All photoresponse values were measured in the reflection mode.

The GaAs photocathode consists of a 7056 glass window onto which an anti-reflection coated AlGaAs/GaAs heterostructure has been bonded. The AlGaAs layer is on the order of 0.5 µm thick. The GaAs layer is on the order of 1.5 µm thick. Both of the epitaxially grown layers are Zn-doped to an acceptor density of $\sim 1 \times 10^{19}$.

Figure number one shows the results of the activations. A Pd deposition on the order of 5 Å thick results in a ~95% loss in photoresponse.

The photocathode which received a nominal Pd deposition of 5.6 Å was sealed to a proximity focused phosphor-screened photo diode. The parallel planes of the cathode surface and the aluminized phosphor screen are separated by a nominal gap of 0.055 in. This tube is designated 9B35.

A second tube also incorporating a 5.6 Å Pd layer was heat cleaned to a slightly different schedule was also sealed. This tube is designated 9C35.

Line Item B: Photoresponse as a function of Re-heat clean temperature.

The cathode of line item A which received a nominal Pd deposition of 8.4 Å, was re-heat cleaned and activated at progressively higher heat clean temperatures. Figure number 2 shows the results. The 20 °C data point is the original activation and is shown only for reference. As figure # 2 shows, initially, significantly improved photoresponse values were obtained. The trend toward increasing PR with hotter heat cleans continued up through the hottest measured heat clean (486 °C). The trials were halted at this temperature in order to minimize the risk of process equipment damage. The temperature was monitored via a 0.010 in. diameter thermocouple which was immersed in a molten pool of indium which surrounds the active area of the GaAs photo cathode.

This photocathode was sealed to the phosphor diode designated 9A35.

Line Item C: Nitrogen exposed Pd coated photo cathode.

The intent of this line item was understood to be to attempt to determine the viability of transporting a Pd coated GaAs photocathode from Intevac to SLAC where it could then be re-heat cleaned and activated. Toward this end, a photo cathode was heat cleaned and metalized with a nominal Pd thickness of 8.4 Å. The photocathode was then vented to room pressure nitrogen. In addition to the room pressure nitrogen, the photocathode was exposed for a period of two minutes to the air in the lab. This was done to mimic the oxygen and water exposure which would inevitably occur during such a transfer. The cathode was then reheat cleaned at ~486 °C and activated to a peak photoresponse of 165 µA/L. This compares favorably with the photocathode which received an 8.4 Å Pd deposition and multiple heat cleans, reported on in line item B, without an exposure to lab air.

This photocathode was sealed to the phosphor diode designated 9D35.

Figure # 1 Peak photoresponse of Pd coated, CsO activated GaAs photocathodes as a function of Pd thickness.

Photoresponse vs Re-Heat Clean Temp.

Figure # 2: Peak photoresponse as a function of re-heat clean temperature for a GaAs photocathode coated with $\sim 8.4 \text{ \AA}$ of Pd.

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