Near IR Photocathode Development

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ABSTRACT

This paper reports on the development of transmission mode Transferred Electron (TE) photocathodes with quantum efficiency in excess of 10% which function in the 950 - 1700 nm wavelength range. Photocathode device physics will be briefly covered along with sealed tube photocathode performance. Results will be presented for both imaging and non-imaging detectors. Measured performance characteristics include: photocathode spectral response, dark current, image tube resolution, and image quality data. A brief discussion of system applications of this technology will also be presented.

1. INTRODUCTION

Recent results from our program to develop a high sensitivity photocathode for 950 - 1700 nm operation are presented in this paper. Previous results from this program were presented in earlier papers.[1,2,3] In particular quantum efficiencies in excess of 25% from 1000 - 1300 nm were obtained in sealed tubes.[3] In this paper emphasis is placed on optimized operation at 1550 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 also presented from measurements on sealed tubes.

2. TRANSFERRED ELECTRON PHOTOCATHODE DEVICE PHYSICS

The most sensitive photocathodes available today are the Negative Electron Affinity (NEA) III-V semiconductor photocathodes. The basic principle of operation of a transmission mode NEA photocathode is illustrated in Figure 1A.[4] The photocathode consists of a p-type semiconductor activated with a work function lowering Cs-O layer. The Fermi level is pinned at the surface near the middle of the bandgap by surface states 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 exciting an electron from the valence band to the conduction band 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 µm 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.[5] For similar GaAsP photocathodes quantum efficiencies as high as 60% have been

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obtained.[6] The larger bandgap of GaAsP results in greater 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.[7] 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. The measured value of quantum efficiency reported for small bandgap NEA photocathodes is quite small. Typical values reported at 1060 nm for Generation-III image intensifiers are in the range of 0.04% with quantum efficiency dropping rapidly at longer wavelengths.[8,9]

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 relative to the vacuum level 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 photocathode[10] has shown reasonably efficient photoemission combined with the required low dark current emission to be of practical interest.

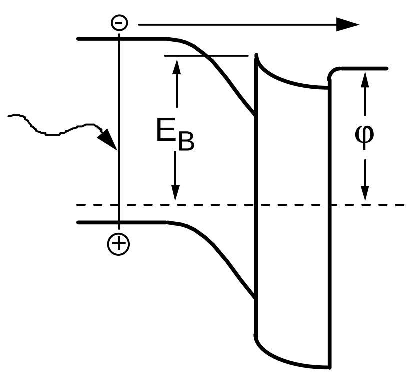

FIGURE 1A. BANDSTRUCTURE OF NEA PHOTOCATHODE

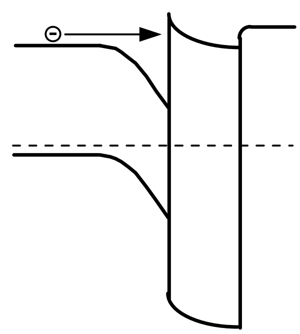

FIGURE 1B. BANDSTRUCTURE OF LONG WAVELENGTH NEA PHOTOCATHODE

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 Varian[11] (and references therein) and more recently at Intevac.[1,2,3]

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 ($In_{0.53}Ga_{0.47}As$ -- 1650 nm) while the InGaAlAs system with the InP lattice constant can generate bandgaps ranging from 1.47 eV ($In_{0.52}Al_{0.48}As$) to 0.75 eV ($In_{0.53}Ga_{0.47}As$). To promote transfer of photoelectrons from the absorber layer over the conduction band discontinuity to the emitter layer, an (AlGaIn)As:Zn grading layer and InP:Si reach-through layer are interposed at the heterointerface. The quaternary grading layer serves to spatially distribute the conduction band discontinuity between the (InGa)As and InP with the reach-through layer providing sufficient electrostatic potential drop to result in a net drop in the energy for conduction band electrons propagating form the (InGa)As absorbing layer to the InP emitter layer.[12] The electron emission layer is a p-type layer of InP. The Schottky barrier is formed by a • 20 Å thick metallic layer activated with cesium and oxygen to lower the work function of the metal to approximately 1 eV.

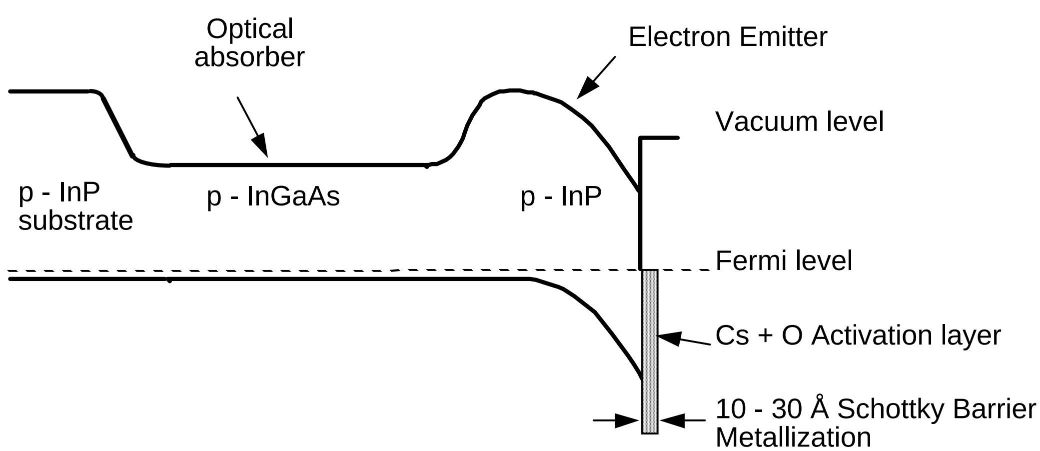

FIGURE 2. BANDSTRUCTURE OF AN UNBIASED TE PHOTOCATHODE

Photocathode operation is illustrated in Figure 3. A reverse bias voltage is applied to the 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.[11]

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 limitations are the free carrier absorption in the p-InP substrate, the electron transmission of the thin Schottky barrier, and obscuration due to the Schottky Barrier contacting grid (Figure 4). 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.

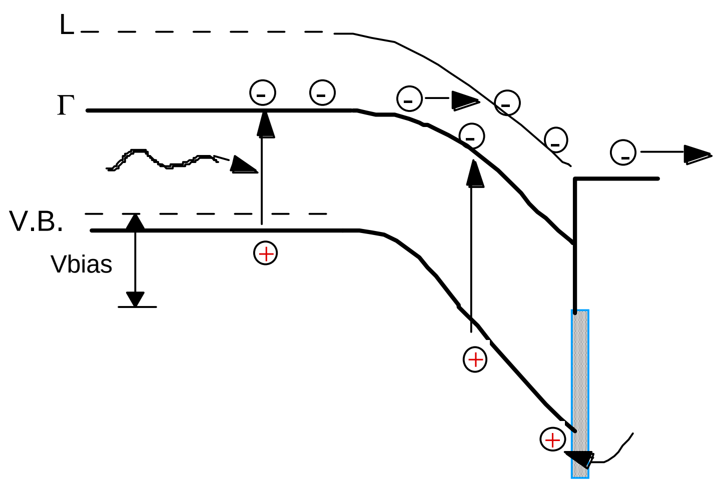

FIGURE 3. BANDSTRUCTURE OF A BIASED TE PHOTOCATHODE

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. PHOTOCATHODE FABRICATION

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 (±0.10°) InP:Zn substrates having hole concentrations of approximately 1.0×10^{17} cm^{-3}. A low substrate doping level is required to minimize free carrier absorption in the substrate at wavelengths longer than 950 nm.

The typical structure consists of an InP:Zn buffer layer, a 1.0 - 1.5 µm thick lattice matched InGaAs absorber layer with a bandgap corresponding to 1650 nm, and an (AlInGa)As grade layer combined with an InP:Si reach-through layer to match the conduction band in the absorber and the InP emitter.[12] Epitaxial structures exhibit good morphologies and uniform doping and alloy constituent incorporation.

Two cathode formats have been fabricated. Imaging applications utilize a photocathode with an active diameter of 18 mm. Detector applications utilize a photocathode with an active format of either 1x1 mm or 2x2 mm. An anti-reflection (AR) coating was applied to the backside of the InP substrate to minimize reflection at 1550 nm. A metal grid consisting of 1.5 µm lines 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 or Intensified Photodiode (IPD)[13] tube to allow photocathode characterization.

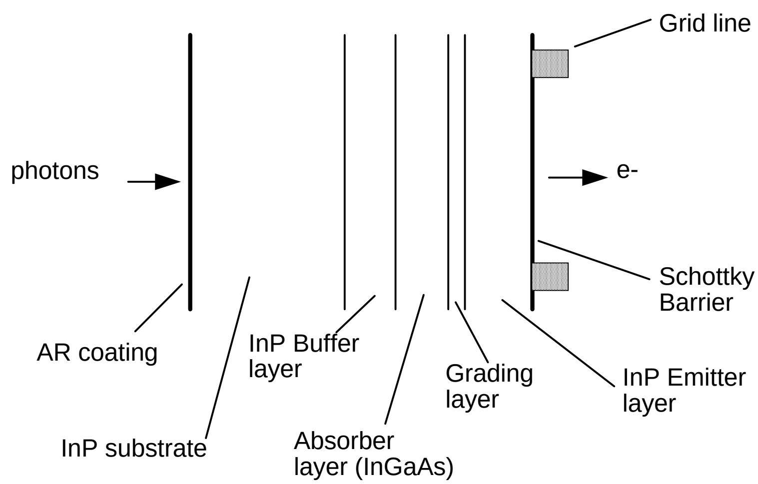

FIGURE 4. TE PHOTOCATHODE STRUCTURE

4. 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 slight roll off in quantum efficiency at longer wavelengths is due to the reduced optical absorption in the absorber layer as the wavelength approaches the absorber layer bandgap.

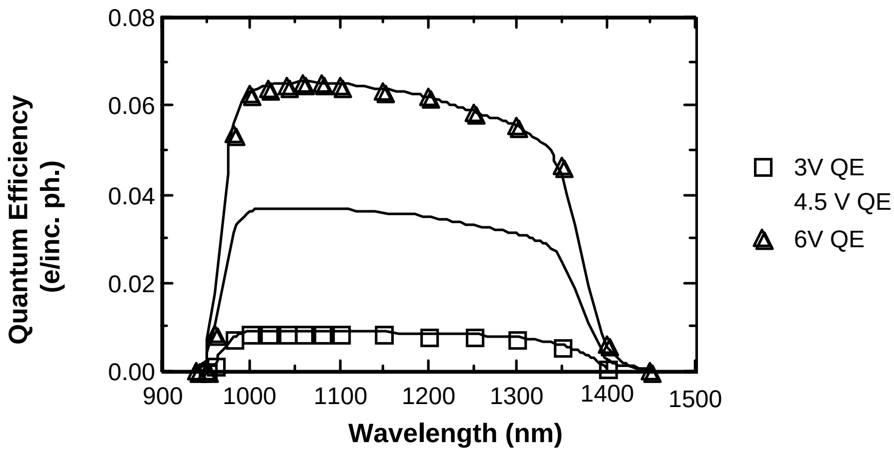

FIGURE 5. QUANTUM EFFICIENCY AS A FUNCTION OF SCHOTTKY BARRIER BIAS, TUBE 9A15

The measured quantum efficiency of several TE photocathodes with various absorber layer compositions is shown in Figure 6. 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 - 20% range. For comparison an S-1, Ag-CsO, cathode has a quantum efficiency at 1060 µm of approximately 0.05% and essentially no sensitivity at wavelengths greater than 1300 nm.

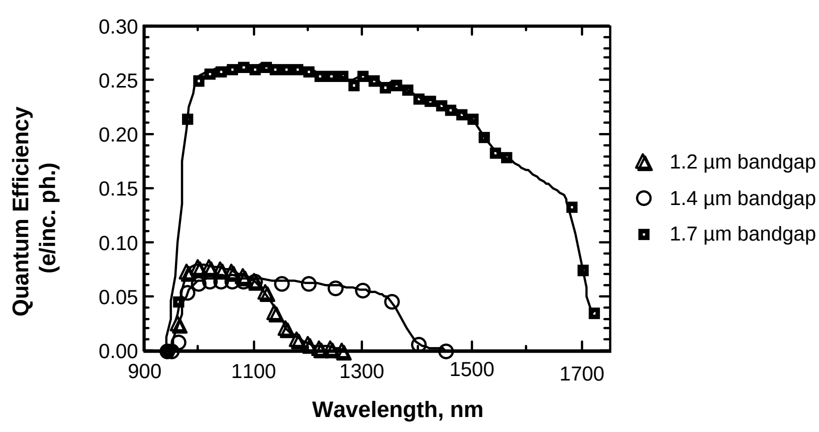

FIGURE 6. QUANTUM EFFICIENCY FOR TE PHOTOCATHODE TUBES WITH DIFFERENT ABSORBER LAYER BANDGAPS AS A FUNCTION OF WAVELENGTH

The dark current and quantum efficiency performance of a photocathode optimized for 1550 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.[14] The quantum efficiency also increases with bias voltage. Two factors cause this voltage dependence. The first is the voltage required to obtain efficient transport across the heterojunction from the InGaAs absorber layer and into the InP emitter. The second is the voltage required to heat the electrons sufficiently in the solid to allow emission into the vacuum.

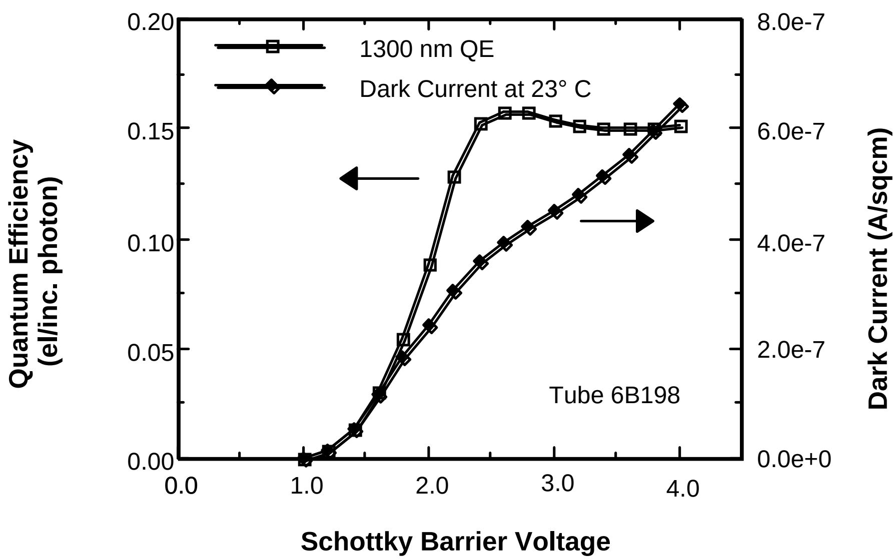

FIGURE 7. DARK CURRENT AS A FUNCTION OF SCHOTTKY BARRIER BIAS

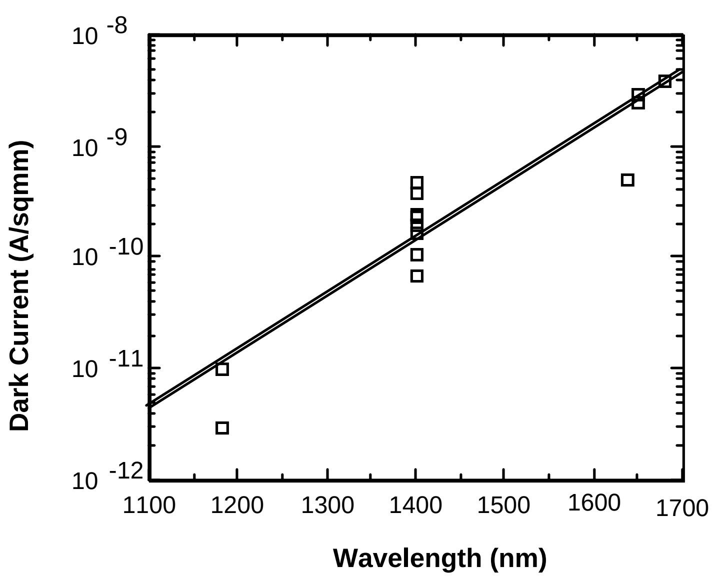

FIGURE 8. ROOM TEMPERATURE DARK CURRENT VERSUS LONG WAVELENGTH CUTOFF

Figure 8 is a compilation of emitted dark current per square mm for a number of photocathodes with different bandgap absorber layers. Absorber layer bandgap determines the photocathode long wavelength cutoff. Dark current increases rapidly as the absorber layer bandgap decreases. This large increase in emitted dark current is due to increased generation in the small bandgap optical absorber layer due to either thermal generation or avalanching. This data also indicates that a substantial advantage can be obtained by tailoring the photocathode structure for a given application. For example a photocathode optimized for operation at 1060 nm could have a cutoff at 1200 nm and dark current emission approximately 2 orders of magnitude less than a photocathode optimized for 1550 nm operation with a cutoff at 1650 nm.

5. TE-IPD PERFORMANCE

The Transferred Electron photocathode Intensified Photodiode[13] (TE-IPD) is a high bandwidth optical detector which could be employed in uses ranging from LIDAR to fiber optic instrumentation such as OTDR equipment or optical waveform recorders. The TE-IPD consists of a 1 mm diameter photocathode electrostatically focused on a 1 mm diameter electron bombarded Schottky diode. Typical operating voltage is 8 kV. At this voltage electron bombarded gain is greater than 1000. The associated excess noise factor is typically less than 1.3. In essence the TE-IPD can be viewed as an ideal avalanche photodiode with regard to some of its external parameters; in particular the high gain, low excess noise factor, and large active area. TE-IPD bandwidth is greater than 500 MHz.

Some of the characteristics of the TE-IPD are shown in Figures 9 and 10. The data shown was measured at room temperature with an applied photocathode Schottky diode voltage of 3.25 V. The photocathode quantum efficiency at 1550 nm was 11% for this bias voltage. The associated emitted photocathode dark current was 5 nA with a measured anode dark current of 5.12 µA at a tube bias voltage of 8 kV.

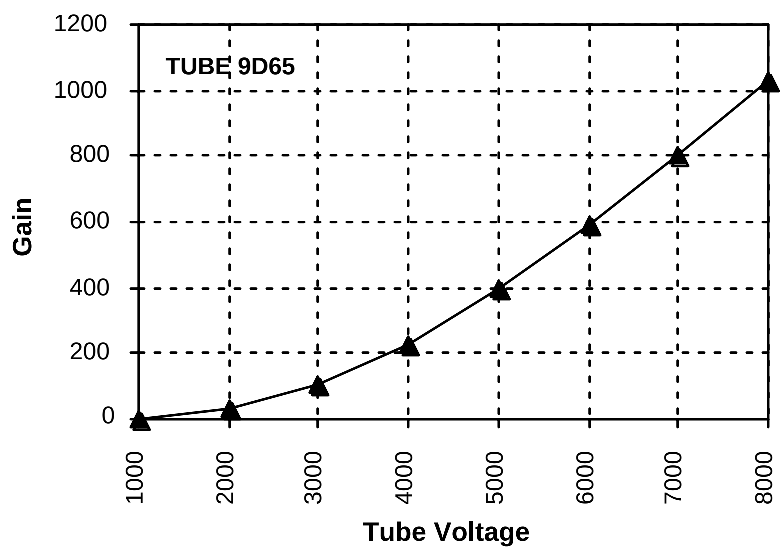

FIGURE 9. TE-IPD GAIN VERSUS TUBE VOLTAGE

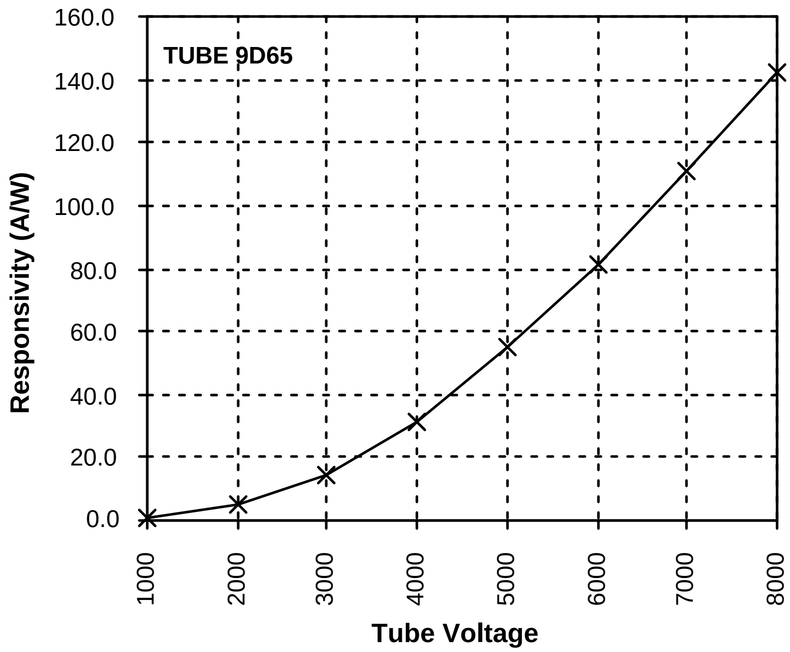

FIGURE 10. TE-IPD RESPONSIVITY AT 1550 NM VERSUS TUBE VOLTAGE

6. TE PHOTOCATHODE IMAGER PERFORMANCE

18 mm format, proximity focused, TE photocathode image tubes have been fabricated at Intevac. The tubes are proximity focused diodes with a P20 phosphor screen on a fiber optic forming the anode of the tube. Typical performance achieved with this tube format is given in Figure 11.

Tube	**9C56**
Photocathode	**InP/InGaAs TE Photocathode**
Tube Format	**18 mm**
Phosphor Screen	**P20**
Limiting Resolution	**23 lp/mm**
Operating Voltage	**4,000 V (cathode to anode bias potential)**
1300 nm Quantum Efficiency	**10% @ 3 V Schottky barrier bias**
Dark Current	**433 nA @ 3 V Schottky barrier bias**

FIGURE 11. TE PHOTOCATHODE PHOSPHOR DIODE IMAGER PERFORMANCE

The low limiting resolution is a function of two factors. The first is the high energy spread of the emitted, hot, electrons from the TE photocathode.[1] The second is the relatively large cathode-to-anode spacing which results from the requirement for two, separate, electrical contacts to the photocathode.

1550 nm quantum efficiency is typically 30% lower than the 1300 nm quantum efficiency reported in Figure 11. This is a result of the lower optical absorption coefficient at longer wavelengths in the InGaAs absorber layer. The 1550 nm quantum efficiency of tube 9C56 was estimated to be 7%.

The TE phosphor diode tubes have been successfully gated by modulating the 4,000 volt cathode-to-anode bias voltage by using a high voltage pulser. Rise times of 100 ns have been achieved which are sufficient to support the system application reported in the next section of this paper.

7. SYSTEM APPLICATIONS

An ideal application of the TE photocathode image tube is in a range gated, laser illuminated, two dimensional imaging system.[1,3] The basic concept for such a system has been in existence almost from the invention of the laser. The significant feature of this embodiment of the concept is the wavelength of operation. The TE photocathode allows operation in the 1500 - 1600 nm band where the eye's tolerance to high intensity illumination is substantially greater than at shorter wavelengths where traditional photocathodes have sensitivity. Hence the term "eyesafe" for laser based active systems operating in this band. The eye safety of this system along with the relative availability of lasers operating in this band will allow much wider deployment of this type of system than in the past.

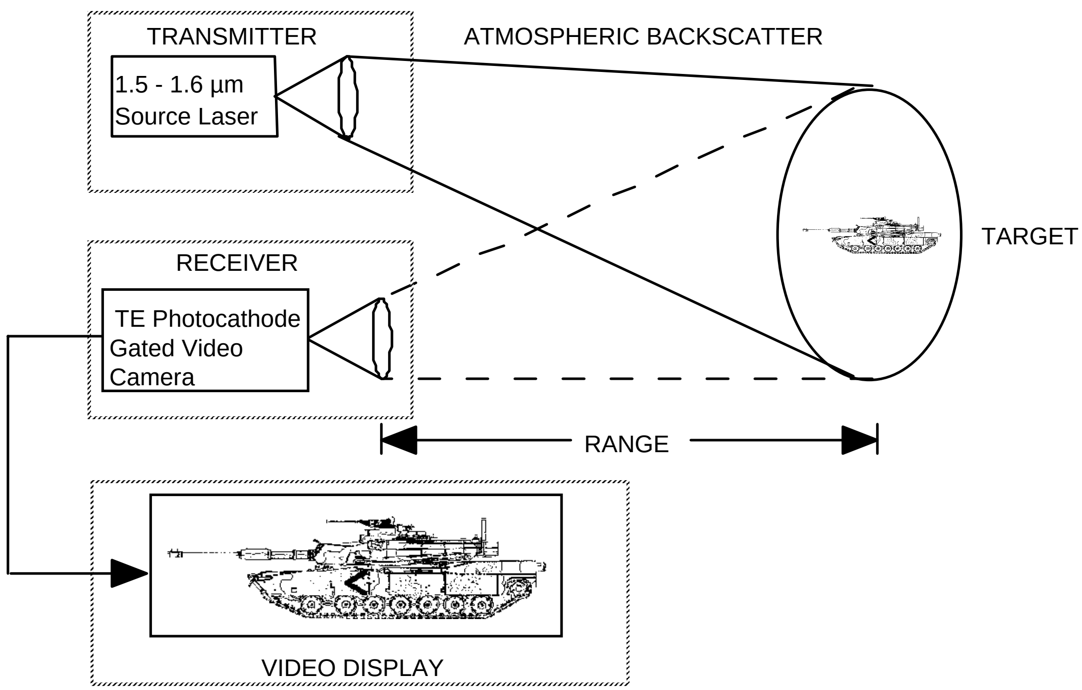

FIGURE 12. BLOCK DIAGRAM OF LASER ILLUMINATED VIEWING AND RANGING (LIVAR) SYSTEM CONCEPT

A prototype system has been constructed to demonstrate this system concept.[15] System features utilized in initial testing are summarized in Figure 13. This simple system allowed target ID at ranges out to 3 Km. Sensor limiting resolution was 350 horizontal TV Lines at the faceplate of the TE photocathode phosphor diode. Sample imagery (single frames with no shot to shot averaging or image processing) obtained with this system is shown in Figure 14.

Laser	Flashlamp pumped, OPO shifted Nd:YAG
	18 mJ @ 1570 nm
	30 Hz rep rate
	beam divergence 0.33° - 1.0°
Optics	2000 mm focal length
	7 inch aperture
	30% transmission at 1570 nm
Gating	Range Resolution 0.5 ft
	Gate width resolution 0.5 ft
	Minimum gate width 100 ns corresponds to 15 ft due to non linear turn on of phosphor diode
Video	RS170 output
	No image processing

FIGURE 13. LIVAR SYSTEM PARAMETERS

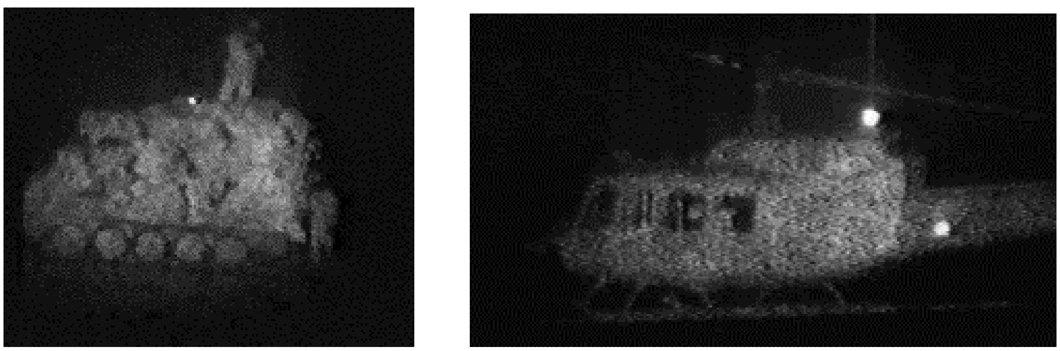

FIGURE 14. LIVAR IMAGERY OF AN ARMORED PERSONNEL CARRIER AT 1200 METERS AND OF A HELICOPTER AT 410 METERS.

8. CONCLUSION

This work has demonstrated the ability of modern semiconductor, "engineered", photocathodes to be optimized for long wavelength operation. It has also demonstrated the viability of the TE photocathode for use in the 950 - 1700 nm wavelength range. Device results for detectors and imagers using the TE photocathode have been presented. A range gated system employing the TE photocathode and an eye safe laser has been successfully demonstrated and is expected to become an important application of this technology.

9. ACKNOWLEDGMENTS

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