Study of Fast, Near-Infrared Photodetectors for the ITER Core LIDAR Thomson Scattering

L. Giudicotti*†, R. Pasqualotto*, A. Alfier*,
M. Beurskens¶, M. Kempenaars¶, and M. J. Walsh¶

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK
**Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, Corso Stati Uniti 4, 35127 Padova, Italy*
†Department of Electrical Engineering, Padova University, Via Gradenigo 6/A 35131 Padova, Italy
¶EURATOM/UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, UK

Abstract. A key component for the ITER core LIDAR Thomson Scattering (TS) diagnostic would be a detector with good sensitivity in the 850-1060 nm near infrared (NIR) spectral region. Covering this spectral region becomes necessary if a Nd:YAG laser system operating at λ =1.06 μm is used as the laser source, which is a very attractive choice in terms of available energy, repetition rate, reliability and cost. In this paper we review the state of the art of two types of detectors available for the above spectral range: the transferred electron (TE) InGaAs/InP hybrid photodiode and the $In_xGa_{1-x}As$ microchannel plate (MCP) image intensifier and we describe the advancements necessary for a possible application in the ITER LIDAR TS. In addition we describe the preliminary characterization of new GaAsP fast MCP photomultipliers (PMTs) suitable for the detection of the visible part of the LIDAR TS spectrum in JET and ITER.

Keywords: LIDAR, Thomson scattering, photoemissive detectors.
PACS: 52.70.-m, 52.25.Os, 85.60.Ha, 95.85.Jq

INTRODUCTION

In the study of a new LIDAR Thomson Scattering (TS) system for measurements of electron temperature and density in the core of the ITER plasma, the need for a detector with adequate quantum efficiency (QE) in the 850-1060 nm wavelength range has been soon recognized. Such a detector would permit to use a Nd:YAG laser system operating at λ=1.06 μm as the laser source, instead of less efficient Ti:sapphire or 2nd harmonic Nd:YAG systems, with clear benefits in terms of available energy, repetition rate and reliability. The key specifications for the ITER LIDAR TS detectors are an active area diameter $D \geq 11$ mm, an equivalent quantum efficiency EQE $\geq$ 6%, and a pulse response time $\tau \leq 330$ ps FWHM.[1] Here EQE is defined as QE/k_F and k_F is the excess noise factor that accounts for any additional noise introduced after the primary detection. At present these specifications can be aimed at only by photoemissive detectors and the two more promising devices so far available are the transferred electron (TE) InGaAs/InP hybrid photodiode and the $In_xGa_{1-x}As$ image intensifier. In

CP988, *Burning Plasma Diagnostics*, edited by F. P. Orsitto, G. Gorini, E. Sindoni, and M. Tardocchi
2008 American Institute of Physics 978-0-7354-0507-3/08/$23.00

this paper we briefly review these two near infrared (NIR) detector technologies and discuss the advancements necessary for their use in the ITER core LIDAR TS system.

THE TE InGaAs/InP HYBRID PHOTODIODE

The transferred electron effect is the electric field induced transfer of electrons from a lower to higher energy valley of the conduction band. In a TE photocathode the extra energy acquired from the electric field is used by photogenerated electrons to overcome the energy vacuum barrier, thus increasing the probability of photoemission.[2] A typical transmission-mode TE photocathode (Fig. 1) is constituted by an absorbing layer and a separate electron emitter. The absorbing layer is made of InGaAs or InGaAsP, lattice matched to InP, and has a long wavelenght cut-off up to λ=1.7 μm, dependent on the material composition. At zero bias the diffusion of photogenerated electrons to the emitter is prevented by a internal ~ 0.6 eV energy barrier. When a reverse voltage is applied, the electric field of the Ag-InP Schottky barrier depletion region extends back into the absorbing layer and the photogenerated electrons can then drift-diffuse into the emitter InP layer, where they can undergo transfer to the upper valley and are eventually emitted into the vacuum.[3] This detection mechanism gives values of QE in the NIR comparable to those of the best visible photocathodes (Fig. 2). This technology has been pioneered by the US company Intevac[4] that at present provides TE hybrid photodiodes suitable for photon counting, two active laser imagers for (military) night vision applications, and an imaging camera for NIR spectroscopy. In a TE hybrid photodiode (Fig. 3) the photoelectrons emitted from the photocathode are accelerated by an external electric field onto a GaAs photodiode where they produce secondary electrons proportionally to the acquired energy.[5-9] This electron bombardment (EB) gain mechanism has a typical excess noise factor k_F = 1.1, thus providing the cleanest amplification so far available for photoemissive detectors. A standard TE hybrid photodiode for photon counting at λ=1.06 μm has a photocathode of 1 mm diameter, and a 0.5 mm diameter, GaAs Schottky avalanche photodiode (SAPD) at the anode. The TE InGaAsP/InP photocathode has a QE in excess of 25% at λ = 1.06 μm, a long wavelength cut-off at λ = 1.33 μm and a dark current i_D = 0.3 pA at –20 °C.[10] Pulse linearity up to 30000 photons/pulse (for 50 ps

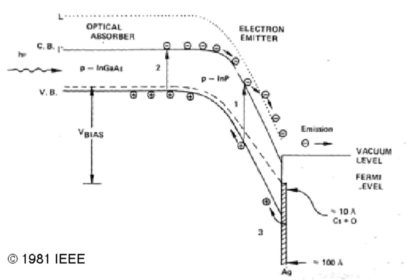

Fig.1 - Schematic of a transmission mode TE photocathode with bias applied (from ref. 2)

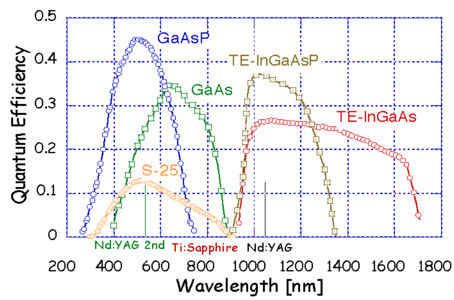

Fig. 2 - Quantum efficiency of visible and NIR photocathodes of interest for ITER LIDAR TS.

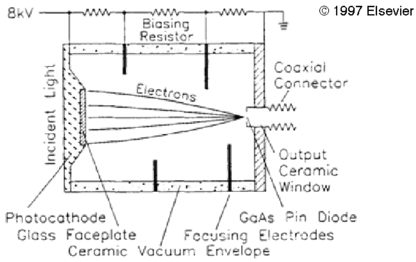

Fig. 3 - Schematic of a TE hybrid photodiode (from ref. 5)

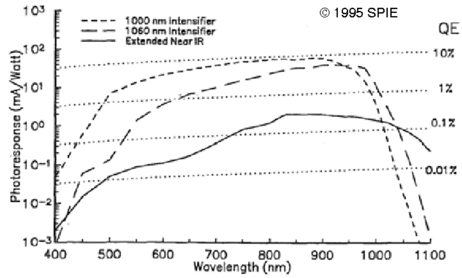

Fig. 4 - Responsivity of $In_xGa_{1-x}As$ photocathodes with different composition (from ref. 10)

pulses) and a gating on-off time of 20 ns have been demonstrated. The pulse response of this detector to a 50 ps source is typically 450 ps FWHM and it is determined by the response time of the SAPD and the time jitter of the photocathode.[3,10] For a larger active area the pulse response becomes dominated by the transit time spread (TTS) of the photoelectrons emitted from different regions of the photocathode. The TTS is ~ 300 ps for a 11 mm photocathode and ~ 800 ps for 18 mm.[3] Therefore the development of a TE hybrid photodiode with 11 mm diameter suitable for the ITER LIDAR TS requires an improved design of the electrostatic focusing and possibly an improvement in the speed of the SAPD and of the photocathode. In spite of these challenging difficulties, the excellent EQE and the large wavelength range make this detector the most interesting NIR device for a future application in ITER LIDAR TS.

THE $In_xGa_{1-x}As$ IMAGE INTENSIFIER

The GaAs photocathodes used in GEN III night vision image intensifiers have a long wavelength cut-off at λ = 900 nm, determined by the 1.1 eV bandgap. But GaAs can be considered as the end point of the ternary system $In_xGa_{1-x}As$ in which the bandgap can be lowered and the sensitivity extended into the IR, by increasing the Indium fraction x. Unfortunately the peak QE also decreases almost exponentially due to an internal interfacial barrier whose height remains approximately constant as the bandgap decreases. These photocathodes are available in commercial image intensifiers and are usually optimized for maximum sensitivity at λ=1.06 μm. This is obtained at x ~ 15% – 20%, resulting in a peak QE<1%. But for LIDAR TS with a ND:YAG source, detection up to the laser wavelength is not necessary and a value x~10% with a cutoff just above 1000 nm and higher QE is more suitable. Fig. 4 shows the spectral sensitivity of two image intensifiers with different composition, developed by Northrop Grumman.[10] Similar photocathodes were also available in image intensifiers by ITT Night Vision. It appear possible that by careful optimization of the composition, $In_xGa_{1-x}As$ can provide a QE ~5% in the spectral region 920 nm – 1000 nm. Due to the low value of x these photocathodes are very similar to GaAs, that has already demonstrated good linearity, speed of response and dark current suitable for LIDAR TS [11,12] and can be easily included in fast MCP PMTs.

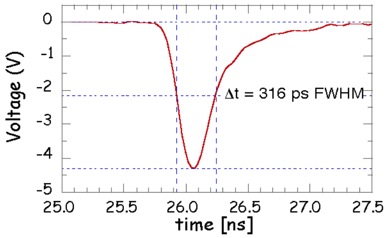

Fig. 5 - Measured pulse response of a fast GaAsP MCP photomultilplier

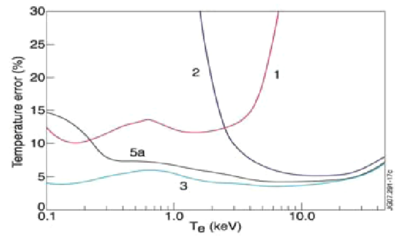

Fig. 6 - Te measurement error calculated for different detector/laser sets: 1) λ=532 nm, GaAsP+GaAs; 2) λ=1064 nm, GaAsP+GaAs; 3) λ=1064 nm, GaAsP+GaAs+TE–InGaAsP/InP; 5a) λ=1064 nm, GaAsP+GaAs+InGaAs.

TEST OF GaAsP FAST MCP PHOTOMULTIPLIERS

Besides the NIR range, in the ITER LIDAR TS a set of detectors is also necessary for covering the visible spectral range down to 300 nm. The JET LIDAR TS systems at present use fast MCP PMTs with either a GaAs photocathode, suitable for operation with 500 nm < λ < 850 nm or a S25 photocathode whose sensitivity extends down to 400 nm, but with lower QE.[11] A relatively new photocathode material suitable for the short wavelength region of the TS spectrum is GaAsP, which shows peak QE~40% (λ = 500 nm) and a QE~10% at λ = 300 nm. This material has never been used in LIDAR TS so far, therefore a set of fast MCP PMTs with a 10 mm diameter GaAsP photocathode has been developed for operation in the JET edge LIDAR TS system, serving also as a test bed for a possible future operation in ITER. The characterization of these detectors is presently under way and preliminary results indicate an EQE~10%, and a pulse response $\tau < 330$ ps (Fig. 5). Fig. 6 shows the expected error on the measured temperature calculated by a simulation of the detected signals and of the associated noise, for different detector sets. These results confirm that with the new NIR detectors and the existing visible MCP PMTs an almost uniform sensitivity over the entire 0.5 – 40 keV ITER design temperature range can be obtained.

The work leading to this article was funded by the European Atomic Energy Community and is subject to the provisions of the European Fusion Development Agreement.

REFERENCES

1. M. J. Walsh, M. Beurskens et al., *Rev. Sci. Instrum.* 10E523 (2006).
2. J. S. Escher, P. E. Gregory et al., *IEEE Electr. Dev. Lett.* **2**, 123 (1981).
3. V. W. Aebi, K. A. Costello et al., *Proc. SPIE* Vol. 2022, 34 (1993).
4. Intevac Inc., 3560 Bassett Street Santa Clara, CA 95054, http://www.intevac.com
5. S. M. Bradbury, R. Mirzoyan et al., *Nucl. Instrum. Meth. A*, **387**,45, (1997).
6. R. A. La Rue, J. P. Edgecumbe et al., *Proc. SPIE* Vol. 2022, 64 (1993).
7. R. A. La Rue, K. A. Costello et al., *IEEE Trans. Electr. Dev.* **44**, 672 (1997).
8. R. A. La Rue, G. A. Davis et al., *IEEE Electr. Dev. Lett.* ***20***, 126 (1999).
9. X. Sun, M. A. Krainak et al., *Proc. SPIE* Vol. 6583, 65830D-1 (2006).
10. J. P. Estrera, T. W. Sinor et al., *Proc. SPIE* Vol. 2551,135 (1995).
11. R. Pasqualotto and P. Nielsen, *Rev. Sci. Instrum.* **74**, 1671 (2003).
12. M. Kempenaars, P. Nielsen et al., *Rev. Sci. Instrum.* **75**, 3894 (2004).