Improvements in the QE of photocathodes

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The basic steps

Optical absorption

Strongly dependent on composition, but predictable from the wavelength dependence of the optical constants

Function of angle of incidence and polarization, particularly beyond the critical angle of ~43 degrees into the window

Excited electron diffusion to the vacuum surface

50% head in the wrong direction unless there is an inbuilt E field. In thin cathodes reflected electrons at the cathode-window surface may still return and escape

Electron escape

Depends on surface states but for 300-500 nm photons (~4 to 2.5 eV) most photo excited electrons will escape

S20 multialkali red sensitive cathodes

Our interest has been in red sensitive PM tubes for materials luminescence and in medicine (particularly cancer optical biopsy of translucent breast tissue around 850 nm). Nevertheless the ideas are much more general.

For S20 at 400 nm a typical tube absorbs ~40% of the light, but <1% by 900nm

Classical QE values of ~20% and <<1% are the result of modest to poor absorption, and 50% of the electrons heading the wrong way

Just by increasing absorption to 100% there are potential gains in QE from ~ 2.5 times at 400 to ~100 times at 900 nm

Further gains could occur with better cathode processing, or with some E field across the S20 cathode

In reality we have achieved >3 times QE improvements at 400 nm, and ~30 times at 900 nm.

These are indicative values, not the ultimate that is possible.

Alternatives

Three obvious routes to improvement are as follows.

1 Make the window act as an optical waveguide so that there is a possible absorption event each time the photon bounces at the cathode interface

Relatively easy via prisms or edge coupling into a planar window, and it can be matched to fibres etc from a spectrometer. Excellent results, even at long wavelengths. (e.g. we used it to record Na emission lines near 1140 nm with an S20 photocathode)

2 With just a single interaction, coupling via a prism can give 100% absorption by careful selection of cathode thickness, polarization and incidence angle
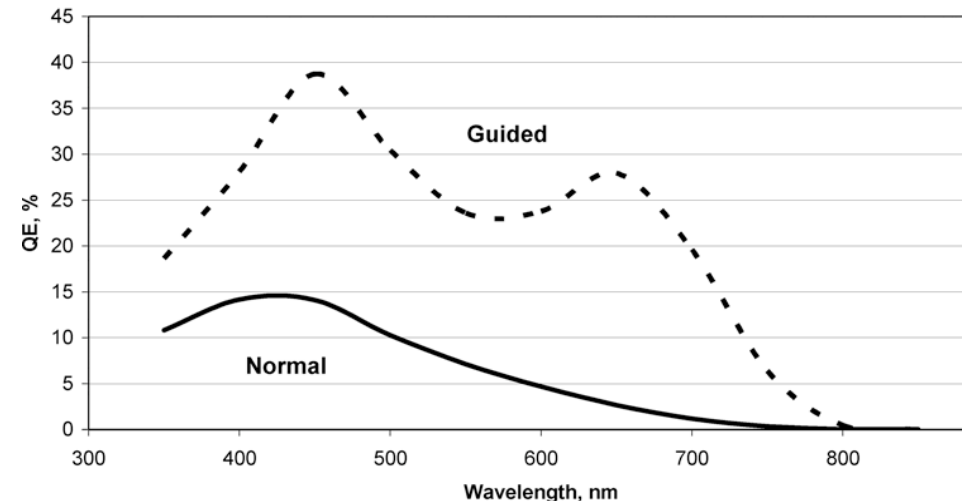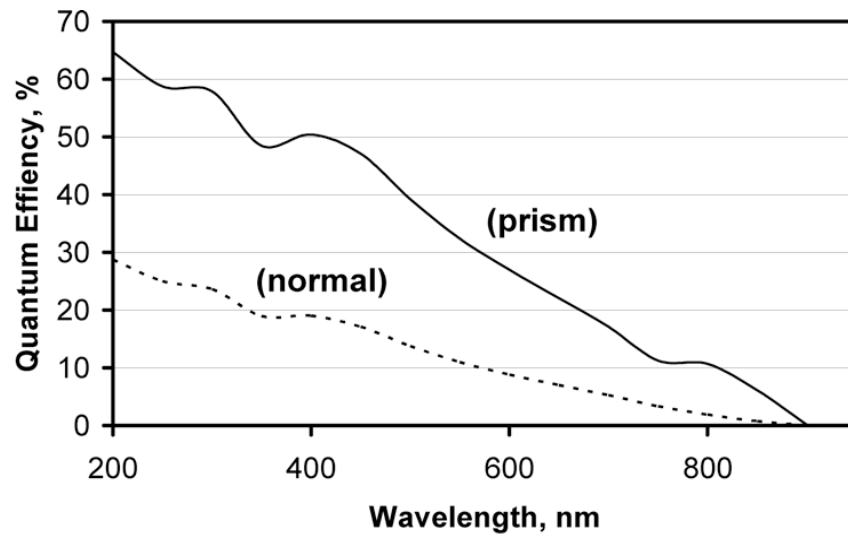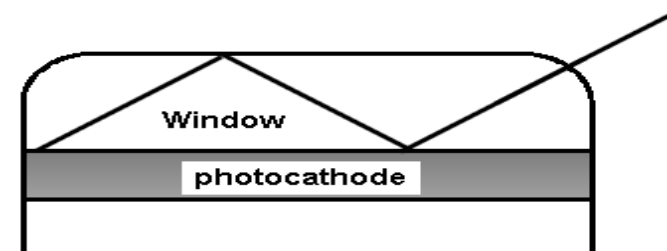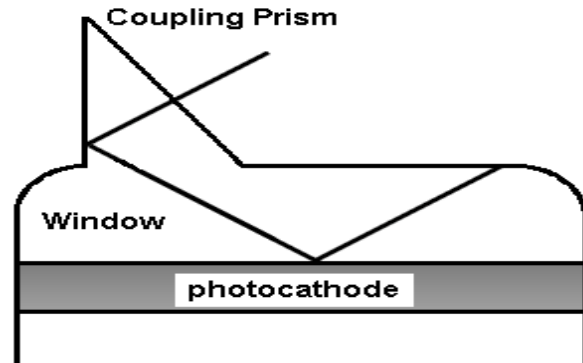
With S20 cathodes we have reached ~70% QE at 400 nm

3 For a planar tube and normal incidence one can still vary the incidence angle on the photocathode by having a structured internal window surface.

Even for our very limited trials we gained 30 to 50% from 300 to 500 nm.

Note also that reflections within the structure offer a second chance at absorption
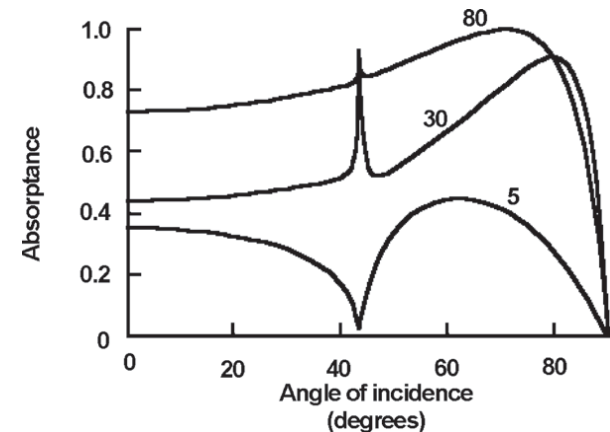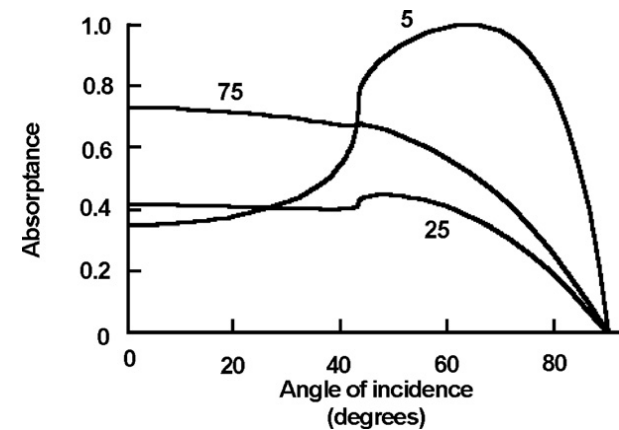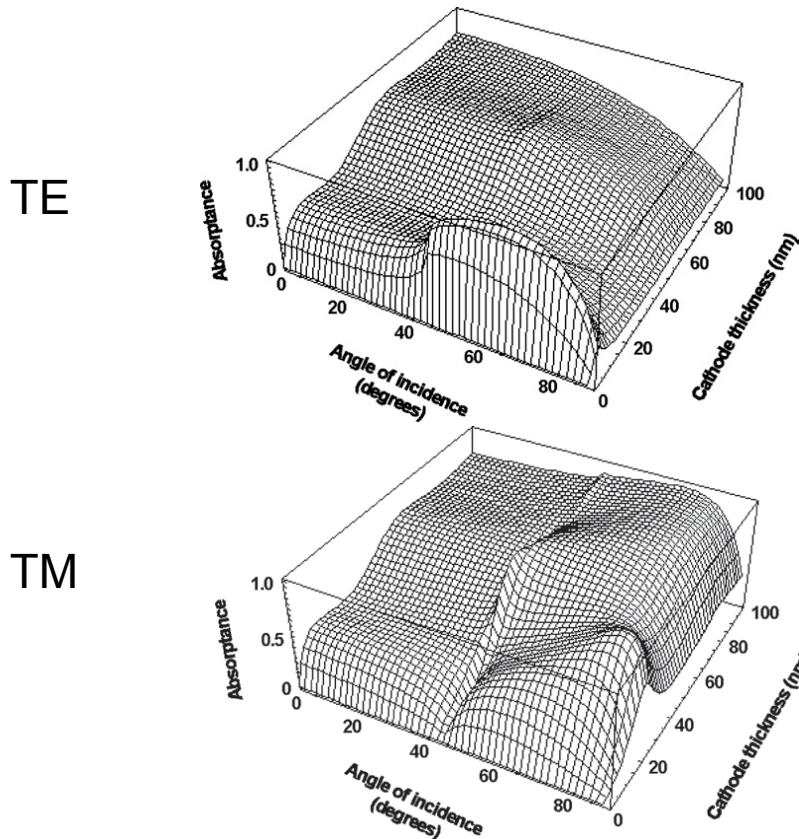
S20 examples from waveguide attempts

Examples from two different types of waveguide design are shown
  Note the RH data were for a poor quality tube
  Benefits are often greatest for the poorer red QE response

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Non-normal incidence

This is the key concept to optimise absorption

It is not intuitive. Thicker cathodes differ in improvements with angle, or polarization.
S20 contour maps of absorption versus thickness and angle of incidence are shown at
400 nm for TE and TM. Angle dependence graphs are for 5, 25 and 75nm cathodes.
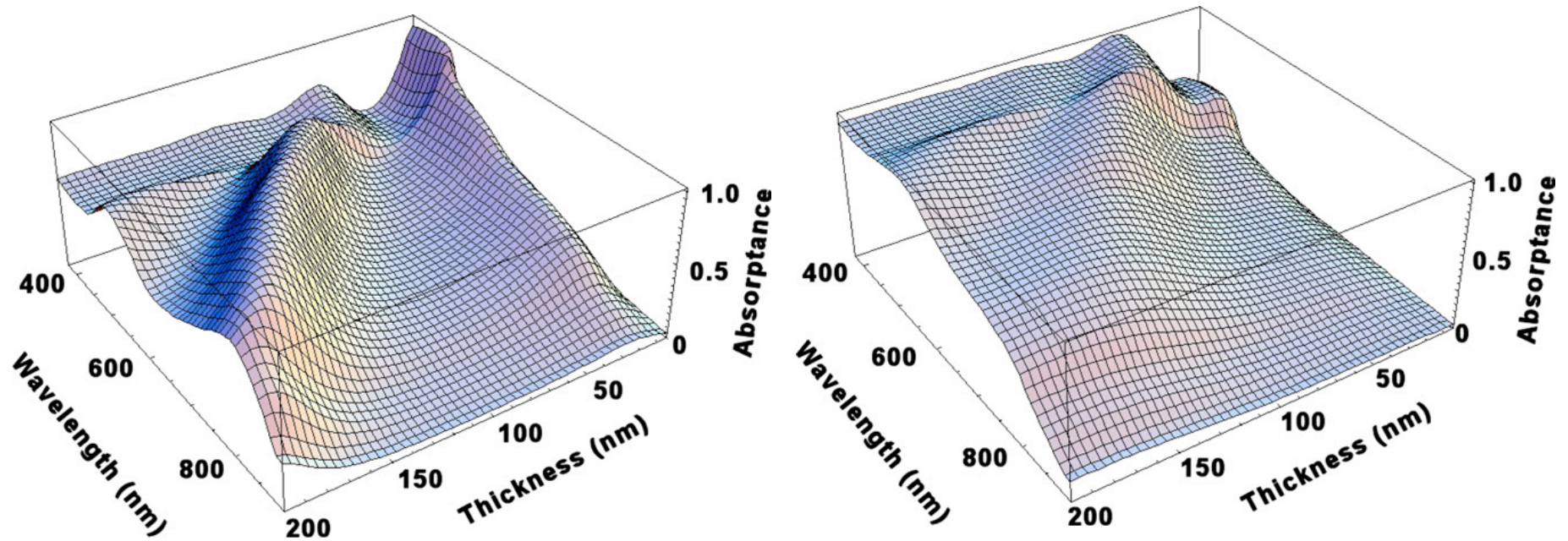

Note dips and spikes at the critical angle; for TE 5nm is best at 60 degrees

Dependence on wavelength

TE and TM patterns differ with wavelength

Here shown for an incidence angle of 55 degrees

Note for TE (LHS) there is a high absorption ridge for very thin cathodes.
Note a sideways step near 500 nm. The peak is ~95% (TE) and ~50% (TM)
One thickness optimisation for 300 to 500 nm is thus feasible, but not for 300 to 900 nm.
NO single thickness which is ideal for both TE and TM, but the thin layer is very good.
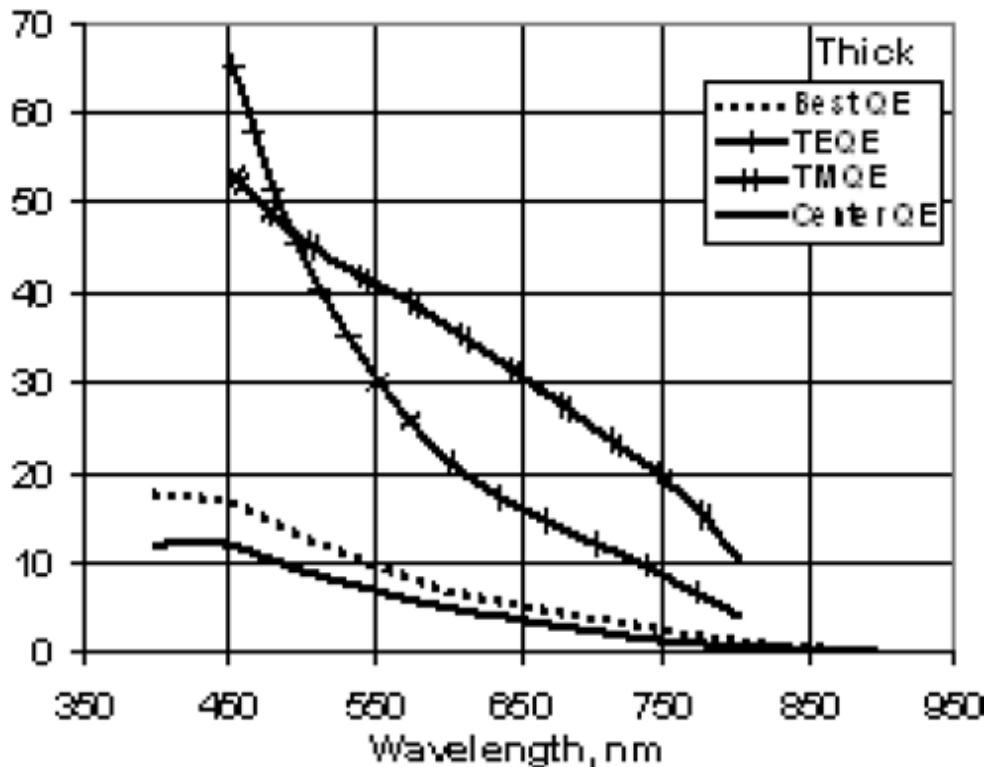There is **NO** thickness which is good for all TM wavelengths.
Thick cathodes would require a very long mean free path for photoexcited electrons

What QE is feasible?

Commercial tubes use normal incidence (so TE=TM) and for S20 tend to be in the range 25 to 60 nm thick

This is too thick for the optimum benefits of incidence at say 55 degrees

To explore optimisation we had a photocathode made of nominally S20 composition which varied in thickness across the face. Mapping this for thickness and incidence angle (and wavelength) gave optimum values in different regions.

The 55 degree angle was mostly good as seen for TE, TM QE on upper lines Normal incidence QE varied as shown in the lower lines (i.e. apparently a poor tube at all points on the surface)
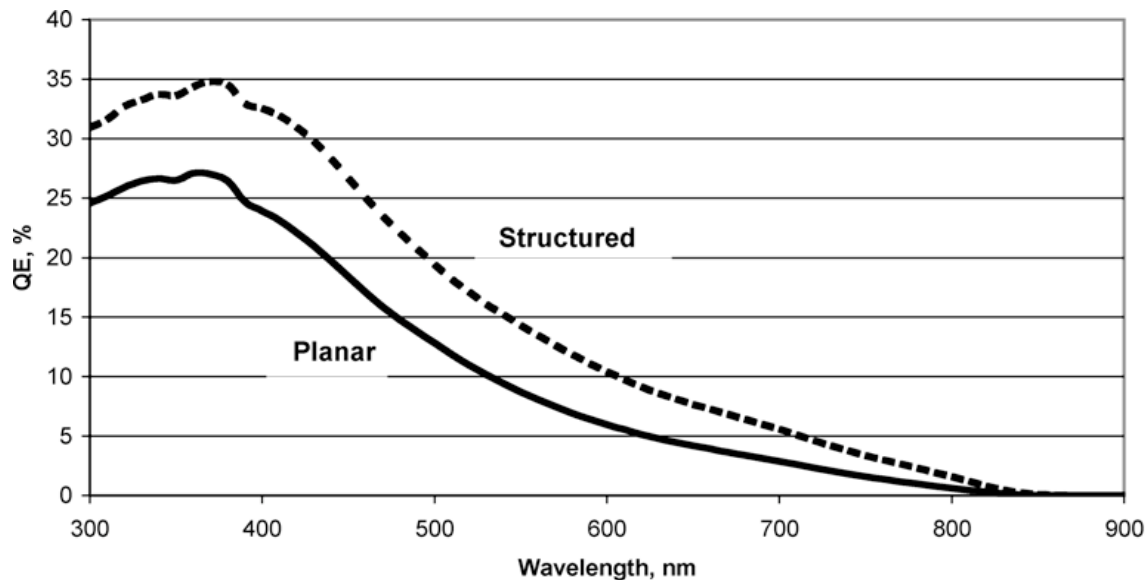
The best QE values are exceptional

A plastic component limited us to 450 nm It was our first attempt so is not optimum S20 composition may be suspect

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Shaped cathode surfaces

Pyramid shapes have been used by pressing into borosilicate glass but at 45 degrees it can be a poor choice of angle, and most benefit is from reflection of non-absorbed light which has a second attempt at absorption.
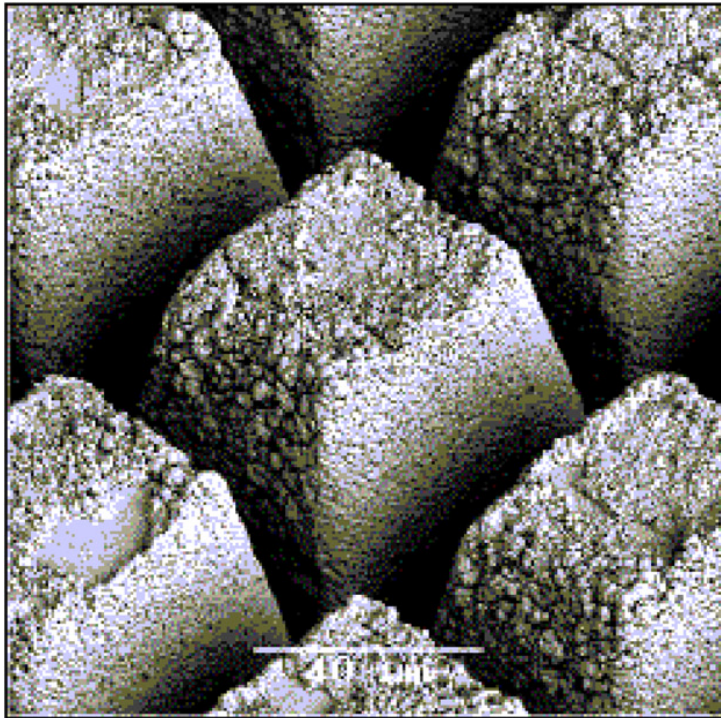
We have used a variety of geometries formed by different processes. One of the more successful was a pattern of 1mm base 60 degree prisms in silica.

A planar region was included to aid S20 deposition so this was not optimised on the pyramids. Hence improvements are merely a clue as to what is possible. Electron extraction from the valleys could improve, and our data indicate some compositional variation into the valleys.
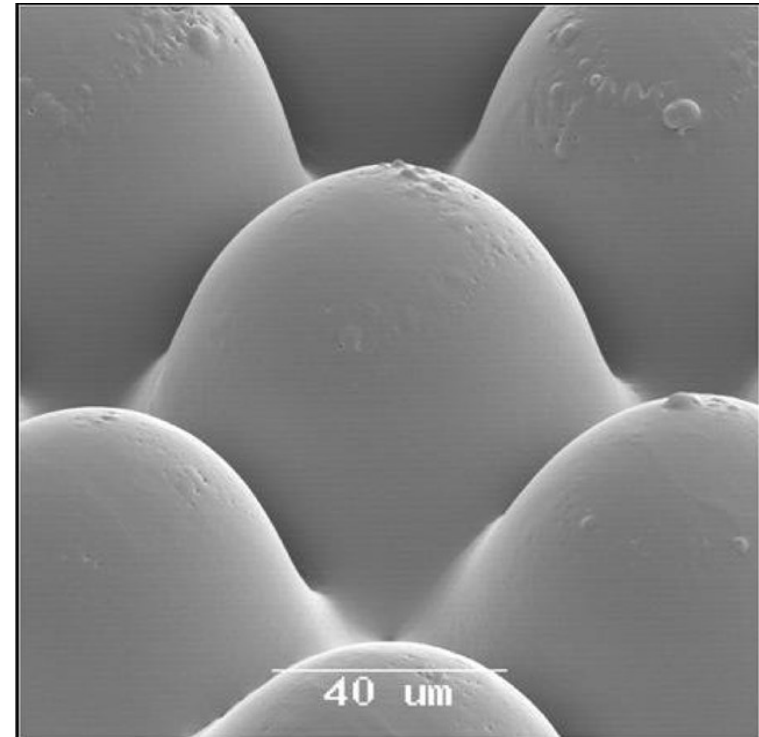
Other structures

We have tried a number of other structures, nearly all showed some enhancement but the number of trials and the critical optimisation of the cathode deposition is quite contentious and needs development.

40 microns

40 microns

The rounded shape aids both cathode deposition and electron extraction
The weakness of the design is that only a limited region of the surface is
giving any enhancement. We recorded a 30 to 50% gain on planar cathodes

Conclusion

For S20 photocathodes it is absolutely clear that the normal incidence performance is far below values that are feasible.

Manufacturers need to rethink how to deposit on structured surfaces and optimisation will not be at the thickness that has been used in the past.

The prediction is that similar enhancements should be feasible for the 300 to 500 nm wavelength range.

If you have questions related to this brief contribution, then please contact me

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