NEW e^- SOURCES SWITCHED BY LASER BEAMS

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Summary : New e^- sources triggered by laser light beams which can produce intense single or multiple bunches of charge (7 to 8×10^{10} electrons/bunch) are under experimental studies in many laboratories of different countries. Their development is needed by many applications as linear collider, free electron lasers, microlithography and realisation such femtosecond streak cameras or RF electron devices as new multimegawatts microwave power sources. Several amperes were recently obtained from such sources in short pulses using different kind of photocathods irradiated by ns or ps light beams. Normalized beam brightness of 10^{10} Am^{-2} rad^{-2} has been measured since 1984.

In this paper we shall try to give an idea of the working principle of such sources and to summarize a part of researchs and realisations on such sources in laboratories such KEK, TEC, SLAC, LANL and LAL which started theoretical and experimental studies since the beginning of the 1980's. Other laboratories as BNL started recently a program of realisation of a new e^- source, CERN and CEA have advanced project to realize in the futur an intense laser driven RF electron gun, we will indicate also some of the realized steps of their programs.

I Introduction

Laser driven electron sources recently developed have similar and many different caracteristics. In fact they use different kinds of photocathodes, different laser systems and different accelerating voltage between the anode and the cathode. But they can produce short electron bunches at the same frequency as that of the laser light beam. Some of them deliver some hundreds of Amp/cm^2 around 100 ps FMHW[1]. Photoemission cannot normally be obtained from any cathode material irradiated by laser beam if its potential barrier is greater than the used laser photon energy $h\nu$. It is possible to observe a very low photoemission as a result of multiphotonic effect, but, in this case, the quantum yield defined as $\eta = \frac{\text{number of produced electrons}}{\text{number of incident photons}}$ is limited to less than 10^{-3}. Most of usual materials (metals, semi-metals or semi-conductors highly p or n doped) have a work function (WF) or a material band gap (MBG) between ϕ_e = 4.5 eV and ϕ_e = 5 eV. Used laser photon energies are in infrared (λ = 1.064 μm) $h\nu$ = 1.181 eV; in green (λ = 0.5320 μm) $h\nu$ = 2.314 eV ; in ultraviolet (λ = 0.3532 μm) $h\nu$ = 3.541 eV and (λ = 0.2660 μm) $h\nu$ = 4.724 eV.

Therefore, the potential barrier of any material must be lowered by at least 2 eV before its irradiation by a laser beam. Many techniques were developed to do it. Potential barrier lowering (PBL) can be obtained chemically by cesiation, electrically by Schottky effect. It is possible also to use heat cleaning effect on some kind of materials like LaB_6 to lower its ϕ_e from 4.6 eV to 2.5 eV.

Photofield emission from metals or semi-conductors is possible with the use of micronic emitters. It operates at high local electric fields by tunnel effect.

In Fig.(1) we give one example of a photoemissive e^- source realized by TEC.[4] Fig.(2) shows an example of a configuration of high brightness photocurrent source studied at San Diego State University.[9]

In principle construction of such sources to deliver intense charge in a time as short as 50 to 100 ps to allow direct injection in S or C band structure is possible, but practically space charge effects are so important that it is not possible to do it without any preliminary pulse compression.

II Photoemission and Photofield emission

2.1 Photoemission

Photoemission occurs from a given material irradiated by a light beam when successively can be realized inside this material photoelectron excitation then a photoelectron diffusion and a photoelectron liberation Fig. 3 shows the process of normal photoemission. Current densities from a given photocathode can be calculated using the general Fowler and Du Bridge formula :

$$J_{P.E.} = \alpha_s \cdot e \int_{-\infty}^{+\infty} N(W_x)\, D(W_x)\, dW_x \qquad (1)$$

where α_s is the absorption coefficient, $N(W_x)$ is the number of electrons which can reach the material surface with an energy which value is between W_x and $W_x + \Delta W_x$. $D(W_x)$ is the transmission probability of the electron in the vacuum solid interface.

Below space charge limit photocurrent densities can be calculated from the expression :

$$J_{PE} = \left(\frac{\eta . e\lambda}{hc}\right) \frac{I_\omega}{\pi r^2} \qquad (2)$$

where η is the quantum yield : $\eta = \frac{N_e}{N_\nu}$ (3)

and $\eta_{eff} = \frac{N_e}{N_\nu(1-\alpha)}$ (4)

where N_e is the produced electrons number

N_ν is the incident photons number

α is the reflexion coefficient of the material

I_ω is the incident optical power at λ wavelength

r is the illuminated spot radius

h is the Planck's constant.

2.2 Photofield emission

Photofield emission is obtained from microscopical emitters working just below field emission threshold (when local electric field $E_{local} = \beta E_{macroscopic}$ is of a magnitude of 0.1 to 0.3 Volt per Angtröm) and illuminated by a laser beam. The caracterization of the photoemitters must be done always in field emission regime by Fowler Nordheim plot. Photofield current density can be calculated from the following general expression :

$$J_{PFE} = N_\nu \cdot \Gamma \cdot \frac{4\pi}{h^3} m_e\, kT \int_{-\infty}^{+\infty} \ln\left[1 + \exp\left(\frac{W-\phi+h\nu}{kT}\right)\right] D(W,F)\, dW \qquad (5)$$

where N_ν is the incident photon number per surface unit,

Γ is the photon electron interaction probability

$kT = eV_T$ is the transverse energy

$h\nu$ is the photon energy at a given λ wavelength

Fig. 4 shows the photofield emission conditions.

Pulsed photofield emission is one of the LAL's[2] choice. BNL[3] is developping a photoelectron source operating on the principle of Shottky effect. Normal photoemission from photocathode of regular size is used at TEC[4], SLAC[5], LANL[6] and KEK[7]. Most of upper indicated laboratories work in picosecond regime, TEC use nanosecond working regime.

Expressions (1), (2) and (5) permit the calculation of "continuous" photocurrent densities. However one can see in the litterature that some authors give peak photocurrent densities to caracterize their e^- source, others give for the same photocathode continuous photocurrent densities. But it is easy to relate the two current densities by :

$$\hat{J} = \langle J \rangle \cdot \tau^{-1} \qquad (6)$$

where $\hat{J}$, $\langle J \rangle$ are respectively peak and continuous photocurrent densities, τ is the pulse photocurrent length.

2.3 Brightness of photoemitted electrons

Brightness of photoemitted electrons can be calculated by the expression[8]

$$B = \frac{J_s\, \mathcal{E}_{cin}}{\pi\, k\, T} \qquad (7)$$

where J_s is the photoemitted current density

$\mathcal{E}_{cin}$ is longitudinal energy $\frac{\mathcal{E}_{cin}}{kT} = \frac{v_e^2}{v_{r_{max}}^2}$ (8)

It is possible to show, in the absence of space charge, that for typical photoemitted electrons, with a transverse kinetic energy eV_T and longitudinal energy eV_L reaching the anode in a solide angle Ω that the effective Brightness can be calculated using the following formula[9] :

$$B = \frac{4\eta\, e\, \lambda\, I_\omega}{h\, c\, r^2\, \pi^2} \left[\frac{V_T}{V_L} + \left(\frac{r}{R}\right)^2\right]^{-1} \qquad (9)$$

where R is the cathode radius, V_L is the anode potential.

2.4 Kind of emission

It can happen that during the normal photoemission process simultaneously thermoelectronic emission occurs due to the incident optical power losses in the material. Temperature rise can also partially or totally damage the photocathode surface. For pulsed illumination of a photocathode by a laser beam with absorbed energy W, the heat transfer theory [10] can be used to approximate the temperature rise by the expression

$$\Delta T \simeq \frac{W}{\pi\, r^2} (2\, K \rho\, C_v)^{1/2}\, \tau^{1/2} \qquad (10)$$

where K is the thermal conductivity, ρ is the mass density, C_v is the specific heat of the material and τ is the pulse duration. In Fig.(5) one can see the importance of temperature rise on tungsten surface when irradiated by a 50 ns pulse from a high power laser

Different kind of emission may start simultaneously during the photofield emission process from a single or from an array of needles as for instance pulsed field emission due to the laser electric field defined as :

$$E_t = K \sqrt{I_\omega} \qquad (11)$$

I_ω in Watt/cm^2 .

Small variation in emitters geometry, especially when they are newly tested may change the field emission threshold and continuous field emission may occur.

Therefore sometimes in laser driven emission it is not easy to know the contribution of different emission processes and their effect on the pulse lengths.

For a normal photocathode the emitted surface is of the same magnitude as the laser light spot, for microcathode the knowledge of the emitted surface is very difficult and is obtained approximatively for a single needle from a Fowler Nordheim plot in continuous field emission conditions.

In the case of an array of needles, the photoemitted surface can be obtained from the FN plot of the laser pulsed field emission.

III Photocathode choice

Dominant parameters which affect the choice of a laser driven photocathode in specific applications are :

- The quantum yield
- The pulse length for an obtained photocurrent (response time of the chosen material vs number of produced electrons)
- The low intrinsic emittance
- The necessity to cesiate or not the photocathode
- The good mechanical stability
- The reproducibility of the photocurrents with the same repetition rate, the same frequency in the same pulse lengths when irradiated with the same I_ω .

LANL and TEC use cesiated antimoine Cs_3 Sb. BNL and LAL are working on metallic and on semi-conducting micronic emitters : W, Nb_3Ti, SiPd, SiW, Si(n) and Si(p). In Fig.(6) we show an example of a micronic emitter used at LAL.

SLAC and KEK operate on cesiated galium arsenide (Cs Ga As) photocathodes. At SLAC, the use of Cs Ga As cathode under circularly polarized light beam at λ = 750 nm lead to the production of limited polarization of photoelectrons beam with a maximum of 50%. Therefore SLAC is doing a serious research effort to develop an alternate photocathode which will be able to deliver photoelectron beams of 100% polarization.

Exploration of semi conductors from II - III - V2 chalocopyrites family as $CdSiAs_2$ or $ZnGeAs_2$; $ZnGeP_2$ and $ZnSiAs_2$ is a very promising way.[10]

IV Used lasers

The laser driven electron sources use generally doubled or tripled pulses from pulsed or CW-wave mode locked or mode locked and Q - switched Nd : YAG lasers.

Continuous wave mode-locked lasers usually produce trains of pulses of more than 70 ps duration at f = 175 MHz.

For applications where shorter pulses are desirable, pulse shortening can be obtained by different techniques for instance higher-harmonic mode-locking. It consists in driving the frequency of the mode-locker by a multiple of the inverse of the cavity round-trip time T . Compression of laser pulses reduces the pulse duration to values of a few picoseconds and even below 1 ps . Picosecond single pulse or train of pulses can be directly obtained from a pulsed mode-locked Nd. YAG by saturable absorbant in different light wavelengths (1ω, 2ω, 3ω). To reach frequencies as high as 3 GHz, 6 GHz and 30 GHz..., multiplexing systems are needed. Optical amplifiers allow to reach desired optical energy in all wavelengths . Fig.(7) shows the KEK's system and Fig.(8) LAL's set up.

V Characteristics of realized laser driven e^- sources

The obtained characteristics of the LOS ALAMOS laser driven RF source are summarized below :

Photocathode	Cs_3 Sb
Quantum yield	$\eta = 10^{-2}$
Laser	: Cw Nd : YAG with 10W average power output in infrared (λ = 1064 nm)
Wavelength	visible (λ = 532 nm)
Pulse duration	100 ps at 108.33 MHz
High voltage	AC Voltage with $V_{max} = 10^6$ Volts
Energy	$\beta\gamma = 3$
Energy spread	$\frac{\Delta\gamma}{\gamma} = \pm 3\%$
$\hat{J}_s$	= 200 A/cm^2

Peak current I[A]	Bunch charge Q[nc]	Normalized Emittance E_n[πmm.mrad]	Normalized Brightness B_n[Am^{-2} rad^{-2}]
100	8	20	$2,5 \times 10^{10}$
130	10	18	4×10^{10}
150	12	32	$1,4 \times 10^{10}$

Table 1

	KEK	SLAC	TEC
Photocathode	Ga As(Cs,0)	Ga As(Cs,0)	Cs_3 Sb
η	5.10^{-2}	5.10^{-2}	10^{-2}
Laser	CW Nd : YAG	ps Nd : YAG	CW Nd : YAG
Optical pulse duration	60 ps	50 ps	60 ns
Wave length λ[nm]	532 and 354	532	532
f [MHz]	2856	2856	1300
High Voltage [KV]	AC Voltage up to 150	DC Voltage 75	50
Peak photocurrent [A]	30		80

Table 2

Photoemitters characteristics obtained at KEK, TEC, SLAC

	BNL	LAL
Photocathode material	Gold-coated tungsten wires of 4μm diameter	W single needles, C, Nb_3 T_i arrays of needles then WS_i Pd S_i microemitters of 1μm diameter
Preliminary working Conditions	Shottky regime at $E_{loc} = 3 \times 10^8$ V/m	Field emission threshold at $E_{loc} = 1$ to 3×10^9 V/m
Γ_{eff}	10^{-4}	0.3 up to 1
laser	quadrupled Cw Nd : YAG	Trippled picosecond Nd : YAG
Optical pulse length	10ps	train of 3 pulses of 15ps each
λ[nm]	266	354
Optical energy	0.7 μJ	40 μJ
Photocurrent density	$7KA/cm^2$	10^9 A/cm^2
peak current	1A	10A

Table 3

Performance of LAL's and BNL's microemitters

Photofield emission studies using semi-conducting emitters have been done at the Lebedev Institute and other Soviet laboratories since the beginning of the 1960's. Important results on photoemissivity of the Ge were obtained and quantum yields of more than one were reached in field emission condition[11]. We present below some figures which summarize the performances obtained in photo field emission from high resistance Silicon and Germanium by the P.G. Borzyak and collaborators [11].

Conclusion

Important progresses are going on the field of high brightness laser driven e^- sources in different laboratories. However, stabilization of the laser amplitudes pulses, when working at high frequencies is not yet achieved. Also many kinds of photocathodes are now tested and no evidence appears about the most performant of them.

Acknowledgment

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References

[1] P.E. Oettinger, "A selection of high-brightness, laser-driven cathodes for electron accelerators and FELS", in Proceedings of the ICFA workshop on low emittance e^-e^+ Beams, BNL March 1987, pp. 20-25.

[2] M. Boussoukaya et al, "Emission de photocourants à partir de photocathodes à pointes", LAL RT/86-04, Septembre 1986.

[3] J. Fischer and T. Srinivasan-Rao, "Short pulse high-current density photoemission in high electric fields", in Proceedings of the ECFA-CAS/CERN-IN2P3/CEA-EPS workshop on New developments in Particle Acceleration techniques, Orsay Vol.II, p. 506, June 29-July 4, 1987.

[4] C. Lee et al, "Practical laser activated photoemissive electron source", Rev. Sci. Inst. 56(4) p. 560, 1985.

[5] James E. Clendenin, SLAC, SLC sources, Private communication.

[6] J.S. Fraser et al, "Electron emission of over $200A/cm^2$ from a pulsed irradiated photocathode", 1985 Particle Accelerator Conference. Accelerator Engeneering and Technology, Vancouver, British Columbia, May 1985, pp. 13-16.

[7] T. Shidara, "Lasertron development and tests of high gradient accelerating structures in Japan", in Proceedings of the ECFA-CAS workshop on New developments in Particle Acceleration Techniques, Orsay Vol. 1, June 29 - July 4, 1987, p. 244.

[8] M. Boussoukaya, A. Septier, "Canon à électron à forte brillance utilisant une cathode en LaB_6", Rev. Phys. App. 11 (1976), p. 603.

[9] G.A. Massey, "Laser photoelectron sources of high apparent brightness", IEEE Journal of Quantum Electronics, Vol. QE-20 n°2, February 1984, p. 103.

[10] H.S. Carslaw, J.C. Jaeger, "Conduction of heat in solids", 2nd ed. Oxford : Clarendon, 1959.

[11] P.G. Borzyak et Al., Phys. Stat. vol. 14, (1966), p. 403.

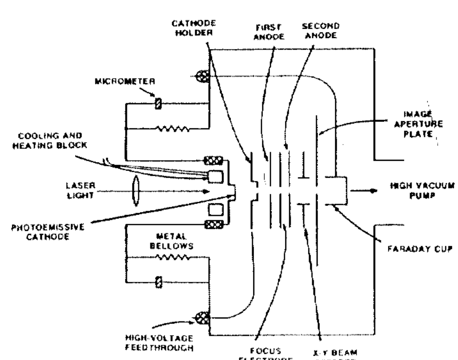

FIG. 1. Schematic diagram of the photoemissive electron source chamber.

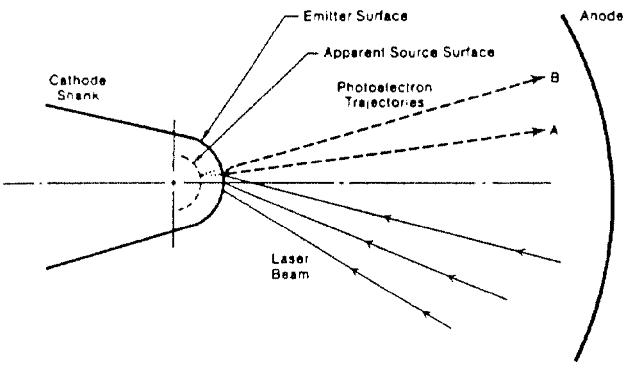

Fig. 2 Configuration of high brightness photoelectron source. Curve *A* is trajectory of electron with no initial transverse velocity. Curve *B* is for an electron with a small initial transverse velocity. The apparent source is to the left of the cathode surface. The electron beam is extracted through a small anode aperture (not shown).

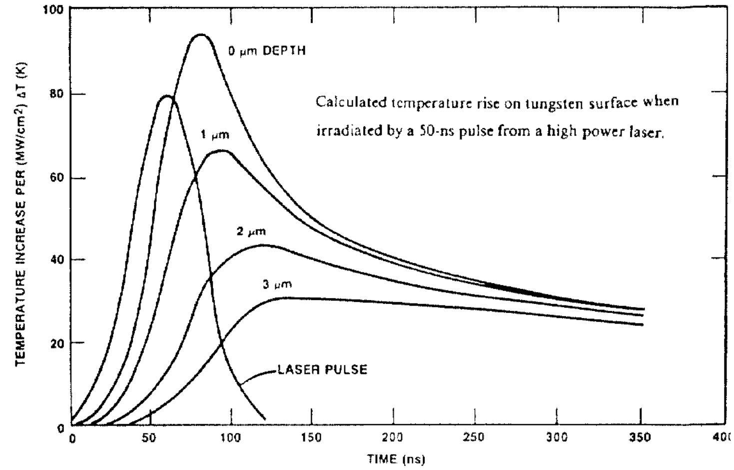

Fig. 5

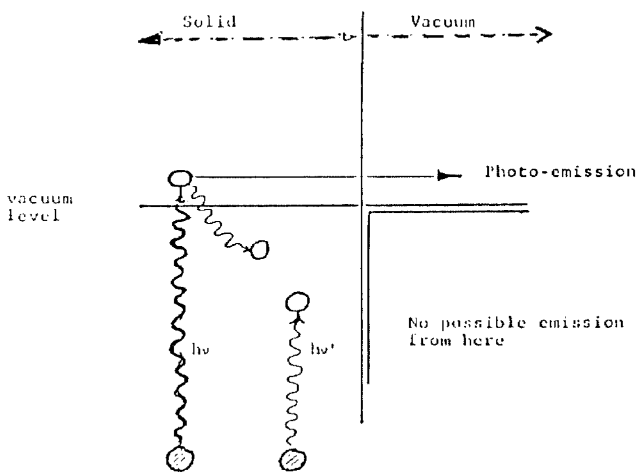

FIG. 3 : Classical Photoemission Configuration

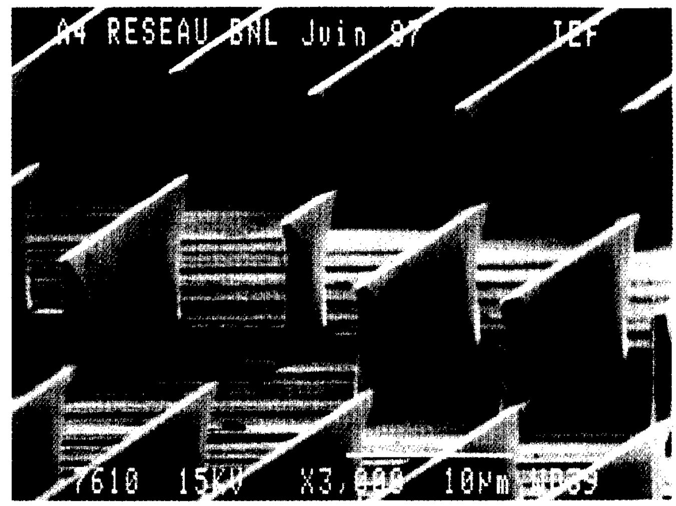

Fig. 6 : WSi microemitters used at LAL

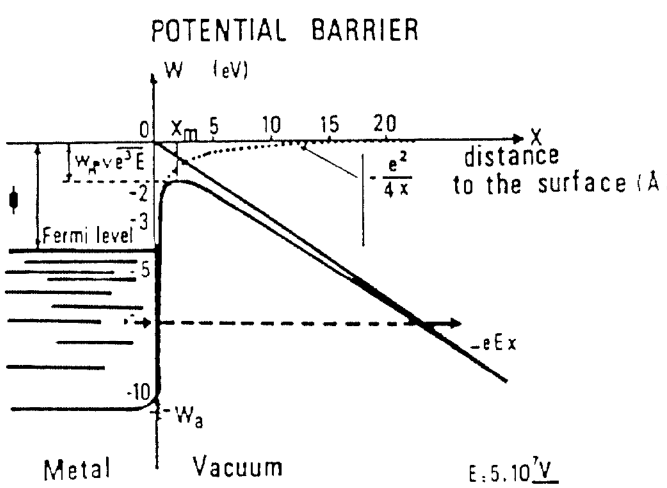

Fig.4 : Potential barrier at field emission regime.

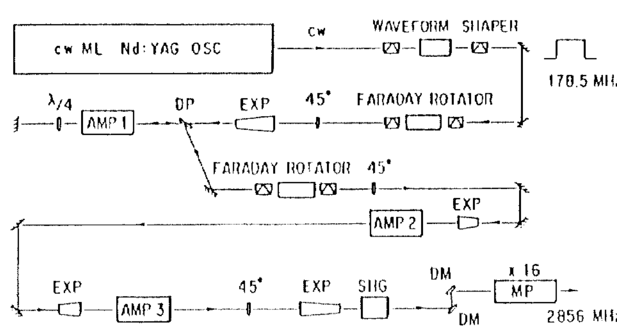

Fig. 7 The configuration of the laser system for lasertron experiment. AMP, amplifier; DP, dielectric polarizer; EXP, expander or reducer; SHG, second-harmonic generator; DM, dichroic mirror; MP, multiplexer

Fig. 8 : Photography of the set up

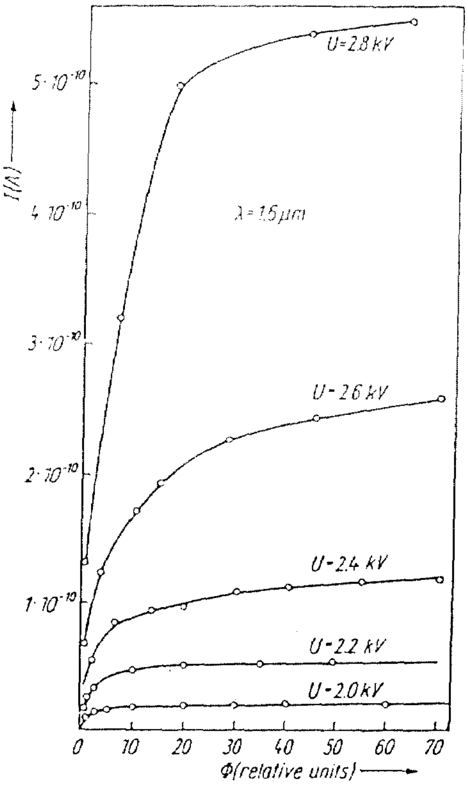

Fig. 10 Light-current characteristies of photo-field-emission for Ge at different voltages (77 °K)

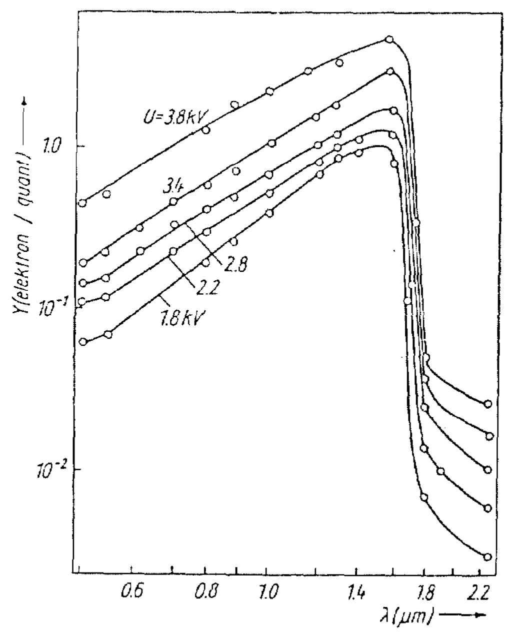

Fig. 9 Spectral characteristics of the quantum efficiency of photo-field-emission from Ge at different voltages (77 °K)

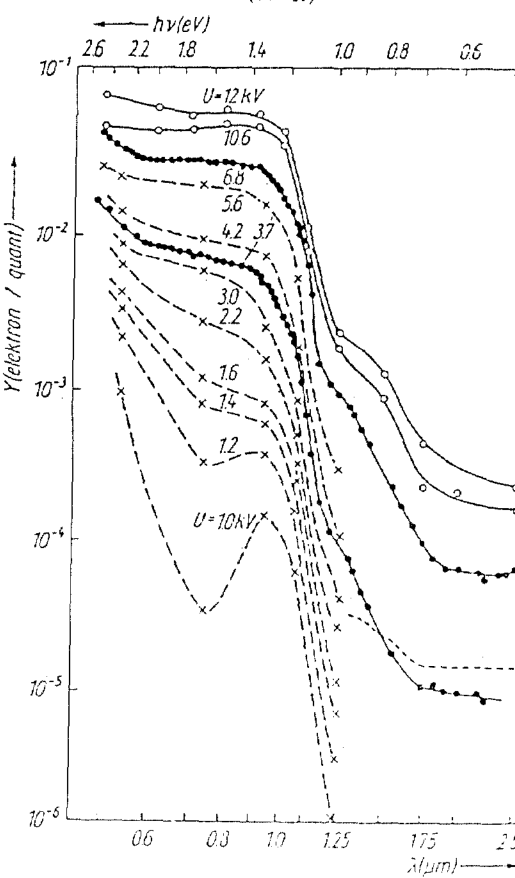

Fig. 11 Spectral characteristics of the quantum efficiency of photo-field-emission from Si at different voltages (77 °K)

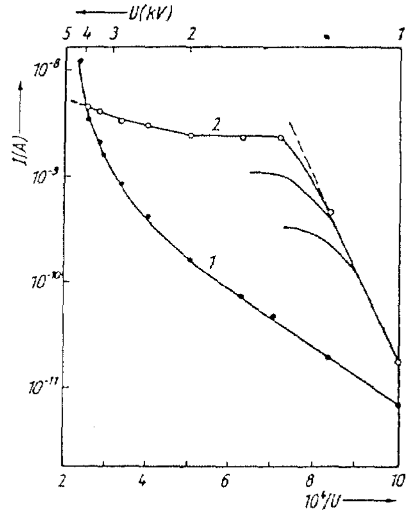

Fig. 12 Current-voltage characteristics of field emission from Ge field cathode. 1 — dark current (77 °K); 2 — photo-field-emission current (77 °K), $\lambda = 1.4\ \mu m$