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LASER EXCITATION IN A GaAs ANODE BY SLOW ELECTRONS

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ABSTRACT: The laser mechanism in a p-type GaAs slab with no junction and a hole concentration higher than 7×10^{18} cm^{-3} is investigated theoretically for the case that the excited electrons are injected from a gas discharge outside the slab. With such an excitation by slow electrons a lower bound of the current density is calculated from the Schawlow-Townes condition. The losses of diffraction and absorption mechanisms are taken into account. Since the slab can be very thin, minimum current densities with laser action of 10 amp./cm^2 are possible. Several absorption and excitation mechanisms are discussed. Their relative importance may be found from the spectrum of the laser light and the depth of the activation zone of the slab.

1. Introduction.

The mechanism of most semiconductor lasers is based on the electron transitions between the conduction and valence band. The lower laser level in p-type s.c. is depopulated by filling the acceptors. In this way the advantages of a 4 level laser are realized. The upper laser level is populated in a p-n laser diode by the electrons from the n-region which are excited when they are pushed through the junction.[1)] Theoretical and experimental work has shown that it is possible to excite a semiconductor without a junction by absorption of light[2)], or by fast electrons[3)], each of which will produce a large number of electron-hole pairs distributed in a relatively deep zone of the semiconductor.

A further method of excitation of the semiconductor using slow electron bombardment to populate the conduction band in a junction-free heavily doped p-type s.c. has been proposed by the author. In the case treated, the semiconductor is a slab with the specifications of a laser cavity situated at the anode of a gas diode. The electrons have primary energies between 0 and 10 eV above the vacuum energy level. Within the semiconductor they loose this energy by radiationless transitions until they reach states in the conduction band. From these states a direct recombination with a hole in the valence band is possible. The most interesting of this paper is that the minimum current density necessary for a laser process is very low when the thickness of the slab is mall enough.

In the following, the theoretical discussion is extended to GaAs to study the possibilities of slow electron excitation. GaAs was chosen since experiments on fast electron excitation seemed to give successful laser action [5)]. Fortunately, the interesting constants for GaAs are better known than those of the I-V semiconductors.

2. Possible Mechanisms.

Before calculating the current density of the bombarding electron discharge necessary to establish a conduction band population suitable for a laser process, it is adviseable to discuss the kind of electron transitions taking place. The transitions are given schematically in Fig. 1 (using the E-k-diagram). If the material is degenerate GaAs of p-type the energy states in the valence band are,(at not too low temperatures T) depopulated down to a certain point A. The energy difference ε_v between A and the top of the valence band is the quasi Fermi level. The energy of A is in all further cases practically identical with the Fermi level of the whole material. In the conduction band a point B is defined with the same k-value as A. Accordingly to Fig.1 ε_v is then the value of a quasi Fermi level in the conduction band when the same number of states are empty as in the valence band.

The electrons injected from the discharge have primary states in the conduction band with an energy higher than the energy at B in the case of GaAs. From the primary states the electrons may reach a state in the valence band by an indirect transition (arrow 2) or by one or more radiationless transitions within the conduction band to a state below B, (arrow 3), and a direct transition (arrow 1) to the valence band. The indirect transitions have in all normal cases a very small probability in comparison to the direct transition, so that for the photon emission process the indirect transitions may be completely neglected.

The emitted photon has the following possibilities:

α) It can be absorbed by the inverse process to 1. One can say that the former position is reproduced giving for the calculation of laser mechanism a longer effective spontaneous lifetime τ .

β) It can induce stimulated emission of another process like that described by arrow 1.

γ) It can be absorbed by an indirect transition corresponding to arrow 4, after which the direct transition (arrow 5) with a smaller photon energy will follow.

δ) It will be absorbed by a process which does not excite an electron across the forbidden band, e.g. by free carrier absorption or intraband absorption.

ε) It will leave the slab.

The processes δ) and ε) give losses in the laser mechanism and are taken expecially into account in determining the laser condition. The others α), β) and γ) are favourable to lasing.

The process γ) produces a disadvantageous shift in the photon energy but it is essential for the discussion of the local distribution of excitation. For a thick slab (i.e. 0.1 mm), the impinging electrons may not penetrate very deeply since the radiationless transitions may be very fast and the driving electric field within the slab is usually small. What, then, would the depth of the lasing action zone be? We might expect this case to be similar to the case of p-n junctions where a thin region of stimulated direct band transitions of conductive excited electrons is expected. A broader active zone is actually observed since the γ)-processes excite neighbouring regions.

The question, " to what a depth will the primary active zone be amplified in the laser?" cannot be answered here. In the following we shall assume that the depth d of the slab is such that the whole material will be activated.

When the question of the depth and the emitted spectrum is studied experimentally one should be able to clear the processes described by γ) implicitely. A thick active zone indicates that the radiationless transitions (arrow 3) take place in small steps. If an energy very little below B is reached a fast direct transition (arrow 1) will follow. If the emitted photon excites the neighbouring region by a process γ) , this would indicate that the absorption (arrow 4) will start from a state very little below A, so that the resulting direct transition (arrow 5) photon energy is only a little different than that of the first transition (arrow 1).

The detailed analysis will also show that the probability of an indirect absorption process is much higher than a direct absorption in contrast to the emission process. A proof of this fact was given 6) in the case of such an absorption that the excited electron can leave the solid (photonemission). It was observed that the excited electrons have a preferential direction perpendicular to the E-vector of the light. This shows in analogy to the Compton effect the participation of the phonons in the indirect absorption process. A direct absorption with a preferential direction parallel to E is much too small to be observed compared with the indirect process.

3. The Laser Condition.

Following the given discussion we shall calculate the minimum discharge current density j at the surface of the GaAs slab at the anode.

We assume a slab thickness d so that it is completely excited. The Schawlow-Townes condition requires that the number N_2 of the occupated states in the conduction band below B must be

$$(1) \qquad N_2 > 2\left(\frac{2\pi}{\lambda}\right)^2 \Delta\nu\, \tau\, V\, \frac{1-R}{l}\, L_a L_d$$

where λ [cm] is the wave length of the laser light, V [cm^3] is the volume and l [cm] is the length of the laser slab, R is the reflectivity of the end surfaces, $\Delta\nu$ [sec^{-1}] is the half width of the band of the spontaneous emission and τ [sec] is the average life time of the excited states for spontaneous emission.

The dimensionless factor L_a takes into account the absorption losses according to process δ) and the dimensionless L_d is related to diffraction losses. N_2 is the overpopulation and is given by the current J of the discharge, so that with the electron charge e

$$(2) \qquad J > 2\left(\frac{2\pi}{\lambda}\right)^2 (1-R)\, \frac{\Delta\nu\, V}{l}\, e\, L_a L_d$$

where the current density is $j = J/O$ (O = Surface area of the slab upon which the electrons impinge) and the slab thickness is d.

$$(3) \qquad j > 2\left(\frac{2\pi}{\lambda}\right)^2 (1-R)\, \frac{\Delta\nu\, d}{l}\, e\, L_a L_d$$

It is very remarkable that through this procedure the life time τ cancels out. If the wave length λ has the value of the GaAs emission ($\lambda = 8400$ Å)

$$(4) \qquad j > C_1 (1-R) \frac{\Delta\nu d}{l} L_a L_d \qquad C_1 = 1{,}739 \times 10^{-9} \frac{\text{amp.}}{\text{cm}^2}$$

The use of $\lambda = 8400$ Å is only a rough assumption. It is, however, sufficient for the following estimations. It is clear that the laser wave length is a little shorter than that determined by the points A and B in Fig. 1. These points are themselves dependant upon the degree of doping.

This blue shift of the emission maximum compared with the spontaneous emission may be an essential difference from the p-n laser diode, where the laser light has a red shift(7).

4. The half width of spontaneous emission.

First of all the fundamental condition that at least one of the two bands is dengenerated must be proved.8)

The density n_e of electrons in the conduction band will be given by

$$n_e = \frac{\tau j}{d e} \qquad (5)$$

If we assume a relative long life time $\tau = 10^{-9}$ sec 9), a small slab thickness $d = 2\mu$ and a high current density $j = 2 \times 10^3$ amp/cm^2 we expect a maximum electron density $n_e(\max) = 6.24 \times 10^{16}$ cm^{-3}. If the kinetic temperature T_{kin} [eV] of the electrons is smaller than the Fermi energy ζ_0 at $T = 0$ then a certain degree of degeneration is given. With T [°K] $= 1,16 \times 10^4 T_{kin}$ and

$$\zeta_{oe} = \frac{h^2}{2 m_{e\,eff}} \left(\frac{3}{8\pi}\right)^{2/3} n_e^{2/3} \qquad (6)$$

one finds

$$T < 5.89 \times 10^{-10} \, n_e^{2/3} \qquad (7)$$

using an effective electron mass $m_{e\,eff.} = 0.072$ 10) for the electron densities n_e up to 10^{17} cm^{-3}.

With $n_e(\max)$ one finds $T < 92,7$°K.

Since it is interesting to get a laser working at 300°K it is necessary to use a GaAs-slab with a degenerate valence band. In analogy to (6) one finds for the case of holes instead of electrons

$$\zeta_{op} = \frac{h^2}{2 m_{p\,eff}} \left(\frac{3}{8\pi}\right)^{2/3} n_p^{2/3} \qquad (8)$$

and in the same way as (7) with the effective hole mass $m_{p\ eff} = 0{,}5$ 11)

$$(9) \qquad T < 8.48 \times 10^{-11}\, n_p^{2/3}$$

To obtain a temperature of 300^{0}K it is necessary to use a material with a hole density of

$$(10) \qquad n_p > 6.6 \times 10^{18}\, cm^{-3}$$

If condition (10) of Fermi statistics is fulfilled the value of the energy level ε_v according to Fig. 1 is 12)

$$(11) \qquad \varepsilon_v = h^2 \left(\frac{3n_p}{8\pi}\right)^{2/3} \frac{1}{2m_{p\,eff}}$$

and hence

$$(12) \qquad \varepsilon_c = h^2 \left(\frac{3n_p}{8\pi}\right)^{2/3} \frac{1}{2m_{e\,eff}}$$

For the whole spectrum of spontaneous recombination the radiation lies between E_3 and E_1. It is obvious from Fig.1, the half width $\Delta\nu$ of this line is smaller than $(\varepsilon_v+\varepsilon_c)/2h$ so that

$$(13) \qquad \Delta\nu < \Delta\nu_0 = \frac{h}{4}\left(\frac{3n_p}{8\pi}\right)^{2/3} \frac{m_{e\,eff} + m_{p\,eff}}{m_{e\,eff}\, m_{p\,eff}}$$

As the density dependence of $m_{e\ eff}$ is not improtant in all interesting cases, one finds with $m_{e\ eff} = 0{,}072$ 10), $m_{p\ eff} = 0{,}5$ 11) and $[n_p] = cm^{-3}$

$$(14) \qquad \Delta\nu_0 = 6.985\, n_p^{2/3}\, sec^{-1}$$

5. The Diffraction Losses.

If a very thin slab is used it seems at first to be necessary to take into account a large loss by diffraction similar to the case of the thin lasing junction zone of a p-n-diode. Within the diode the refractive index does not change very much so that a light beam which is incident perpendicular to one end will be diffracted partly into the non-lasing regions of the crystal. This may be the reason why with the best pumping conditions efficiencies of only 2% are reached 7). In opposition to this case of the diode the whole lasing slab is limited by the strongly refracting surface. According to Fig. 2, where the slab is drawn as a rectangle, a radiation bundle incident normally to the left end will be diffracted after reflection so that the first minimum lies in a direction given by the complement of the angle α. It is usual in similar cases to treat the questions of diffraction only with respect to the intensities within the first minima. A wave front in the direction of the first minimum has an angle α of incidence with respect to the upper or lower surface of the slab. Total reflection with a refraction index n will take place when

(15) $$\sin \alpha > 1/n \, .$$

Since is given by

(16) $$\cos \alpha = \lambda / dn \, ,$$

no diffraction losses will rise if

(17) $$d > d_0 = \frac{\lambda}{\sqrt{n^2-1}}$$

In the case of GaAs with = 8400 Å and $n = 3.3$ 13)

$$d_0 = 0.267\mu \tag{18}$$

This result shows that the diffraction losses are negligible even for very thin slabs.

$$L_d = 1 \tag{19}$$

The whole slab acts like a wave guide with total reflecting walls to the radiation. It is important that the conduction material below the semiconductor has an index of refraction n_b sufficiently smaller than that of GaAs at 8400 Å. For example, properties of a wave guide are fulfilled with $n_b = 3$ if the thickness d is greater than 1.795μ .

6. The Absorption losses.

The factor L_a in the equations (1) to (3) incorporates the effect of the processes δ). L_a is the intensity of a wave when it is starting at one end of the slab to that after one passage along the length ℓ . With an absorption coefficient k^* due to these losses one finds

(20) $$L_a = e^{k^* \ell}$$

The detailed description of the processes δ) may be treated for the free-carrier absorption in the same way as for the case of Cs_3Sb 4). In GaAs, the intraband absorption is comparatively high, analogous to Germanium 14).

A further absorption mechanisms of the type δ) may be possible, we shall use for GaAs an empirical value of k instead of a theoretical value. The total absoortion coefficients of p-GaAs with 10^{19} to 10^{20} holes/cm2 were measured by Kudman and Seidel 15). The special absorption coefficients k^* at 1.47 eV can be eliminated by the prolongation of the linear parts in the logarithmic absorption spectrum to 1.47 e.V., at which the difference from the much higher coefficients measured are due to processes δ) . These must be subracted to get the absorption coefficient due only to processes δ) . The empirical values for k can be approximated by

(21) $$k^* = 3.87 \times 10^{-21} n_p^{1.16} \quad (5 \times 10^{18}\,\mathrm{cm}^{-3} < n_p < 10^{20}\,\mathrm{cm}^{-3})$$

7. Results.

Summarizing the results of (4), (14), (19), (20) and (21) we get a condition for the current discharge density j which should give a laser process in the GaAs anode. With lengths in cm, masses in g and $e = 1{,}602\times 10^{-19}$ Coulomb we find

$$(22) \qquad j > j_0 = \frac{\pi^{4/3}}{2}\,\frac{eh}{\lambda^2}(1-R)\frac{d}{l}\,\frac{m_{eeff}+m_{peff}}{m_{eeff}\,m_{peff}}\,n_p^{2/3}\,e^{3.87\times 10^{-11} n_p^{1.16} l}$$

$$j_0 = 1.25\times 10^{-8}\,\frac{(1-R)d}{l}\,n_p^{2/3}\,e^{3.87\times 10^{-11} n_p^{1.16} l}$$

Notice that j is not the smallest value for which a laser process may arise but only a lower bound. The smallest current density j with resulting laser process can only be given, if the precise value of $\Delta\nu$ is known. Here, only a higher bound was used.

In Fig. 3 the dependence of j upon l with n_p as parameter is given for the case of a reflectivity R =99% . It may be seen that as in the case of Cs$_3$Sb 4) a surprising small current density of 10 am./cm^2 is possible, if a hole concentration of $\sim 10^{19}$ cm^{-3} is used. This is the smallest current density with which it is possible to obtain a degenerate conduction band at 300°K and higher (equ.10). Further the smallest thickness d (from the diffraction condition (19)) and an optimal length of about 0,5 mm are necessary. A higher length than 5mm is of no interest because of (10) (the condition that the hole density $n_p > 6 \cdot 10^{18}$ cm^{-3}) if current densities smaller than 10^4 amp./cm2 are to be reached.

The minimum of current density as a function of the length l [cm] is given by $(\partial j/\partial l) = 0$ and leads to an optimal length l_{opt} given by

(23) $$l_{opt} = 2{,}585 \times 10^{20}\, n_p^{-1{,}16}$$

In Fig. 4 l_{opt} is plotted as a function of n_p. The current density is limited by the thickness d. d has to be greater than the drift length of the electrons in an electric field E with a spontaneous recombination life-time τ. The electron drift is determined by the electron mobility μ_e and the current conduction by the hole mobility μ_p. With the hole density n_p and the electron charge e one finds

(24) $$j < j_1 = \frac{d\, n_p \mu_p e}{\mu_n \tau}$$

Using the extreme values $n_p = 10^{20}$ cm^{-3}, d = 2μ, τ =10^{-9}sec and the values μ_p=200 cm^2/Vsec and μ_e= 3400 cm^2/Vsec at 300°K 16) we find j_1 = 1.34 x 10^5 amp./cm^2. This limitation is high enough for the interesting cases. In special cases of lower hole density it is still higher.

A further necessary condition for equation (22) is that the thickness d be greater than the free path of the electrons in the conduction band. The difficulties in analysing the interaction of electrons with an energy from 0.001 to 5 ev are well known.(e.g. from the secondary electron emission 17)). Preliminary information about the mean free path is given by measurements of the depth from which electrons can be emitted by photoemission. These depths are less than 0.2μ for potassium for electrons of energy between 0.005 and 5 ev after their excitation inside the metal 18). The largest depth was for lowest electron energies. The lowest energies of conduction electrons are here of less interest because of the necessary relatively large magnitude of the energy ε_v. Starting from these results the assumption of a smaller mean free path of conduction electrons 2μ holds true.

Questions of cooling the material do not arise when such low current densities as calculated here are applied.

8. Conclusions.

Comparatively small current densities are made possible by the use of very thin slabs. In GaAs diodes the thickness of the active zone is 30 μ and more. For example with a thickness of 20 μ , a normal reflectivity of 70%, a length of 1 mm and a hole density of $10^{19} cm^{-3}$ one finds from equation (22) a minimum current density $j_o = 2.42 \times 10^4$ amp/cm^2. This current is comparable with those used in GaAs diodes. The advantage of the laser anode is that a variation of the thickness is possible and that for the smallest thickness (with respect to the diffraction) comparatively small current densities may give laser action. A further advantage would be the modulation of the laser action by controlling the gas discharge with grids or by means of plasma physics.

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Literature

1) R.N. Hall, G.E. Fenner, J.D. Kingsley, T.J. Soltys, R.O. Carlson, Phys. Rev. Lett. 9 (1962) 366; M.I. Nathan, W.P. Dumke, G. Burns, F.H. Dill, G. Lasher, Appl. Phys. Lett. 1 (1962) 62

2) N.G. Basov, O.N. Krokhin, Soviet Phys. JETP 19, 15=8 (1964)

3) N.G. Basov, Bogdankevich, Devyatkov, JETP (to be published)

4) H. Hora, Intern. Sympos. on Laser Phys. and Applications, Bern, Okt. 1964; physica status solidi 8 Nr. 1 (1965) (in press)

5) C.E. Hurwitz, R.J. Keyes, Appl. Phys. Lett. 5, 139 (1964)

6) H. Hora, Ann. Phys. 10, 243 (1963); Jenaer Jahrbuch 514 (1960, 2nd part); P. Görlich, H. Hora, Izvest, Akad. Nauk SSSR (Fiz-Ser.) 24, 698 (1960)

7) F.N. Hooge, Intern. Sympos. on Laser Phys. and Applic., Bern, Okt. 1964

8) N.G. Basov, Quantum Electronics, III. Int. Confer. Paris, Febr. 1963 p. 1769

9) W. Heywang, private communication

10) I. Kudman, L. Vieland, J. Phys. Chem. Solids 24, 967 (1963)

11) R.J. Bennett, J. Phys. Chem. Solids 23, 1679 (1962)

12) W. Shockley, Electrons and Holes in Semiconductors, Princeton N.J. 1959, p. 241

13) H.R. Phillipp, H. Ehrenreich, Phys. Rev. 129, 1550 (1963)

14) R. Kessler, physica status solidi 5, 3 (1964)

15) I. Kudman, T. Seidel, J. appl. Phys. 33, 771 (1962)

16) O. Madelung, in S. Flügge's Handb. Phys. vol. 20 p. 238, Springer, Berlin 1957

17) O. Hachenberg, W. Brauer, Advances in Electronics and Electron Physics 11 (1959) 413.

18) H. Mayer, H. Thomas, Z. Phys. 147, 419 (1957)

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Fig. 4 - Optimal slab length l_{opt} for smallest current densities in dependence upon the hole density n_p.

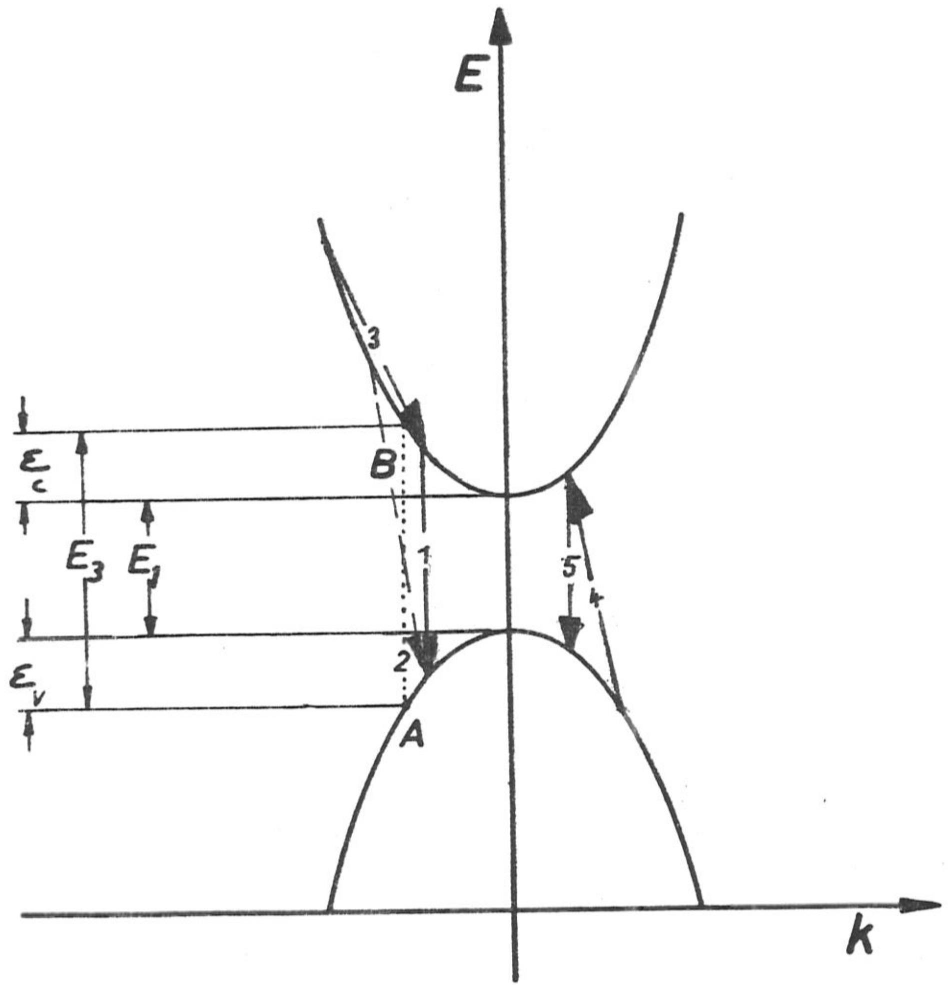


Fig. 1

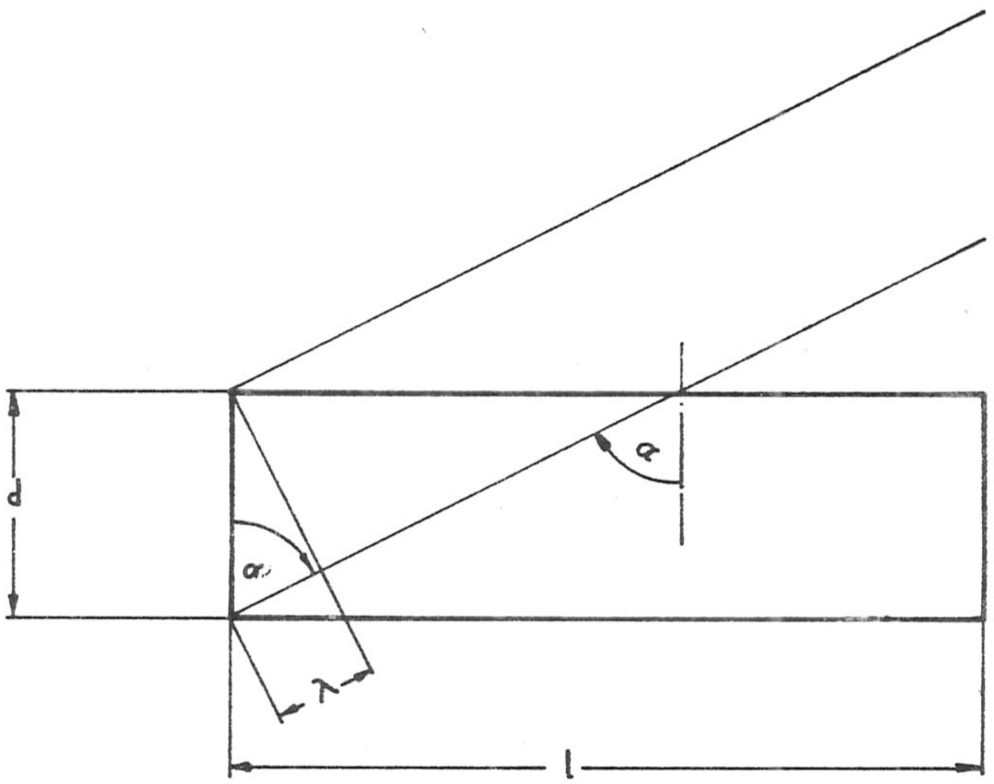
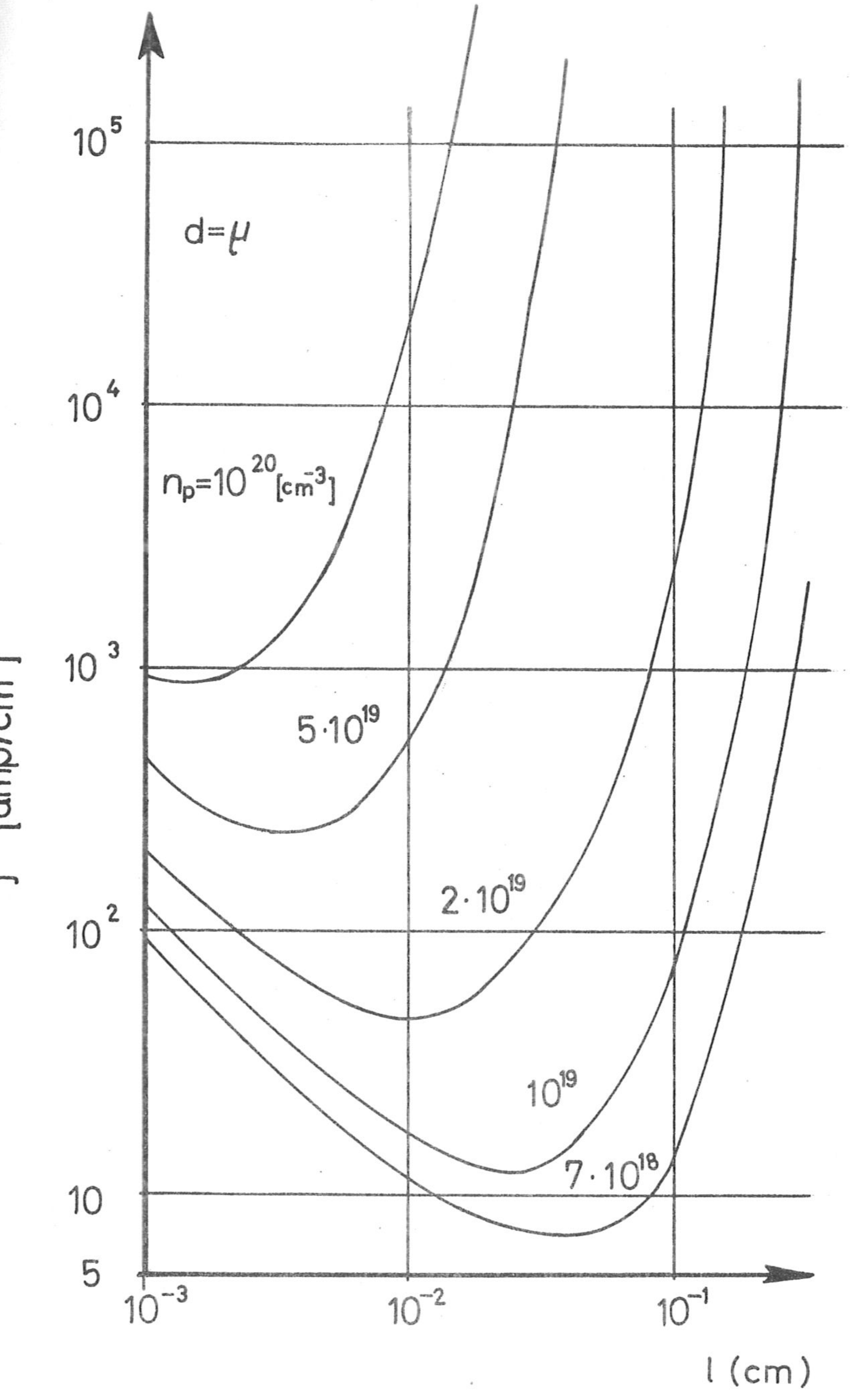


Fig. 2



j [amp/cm²]
10^5
10^4
10^3
10^2
10
5
10^{-3}
10^{-2}
10^{-1}
l (cm)
d=μ
$n_p=10^{20}\,[cm^{-3}]$
$5\cdot10^{19}$
$2\cdot10^{19}$
10^{19}
$7\cdot10^{18}$

Fig. 3

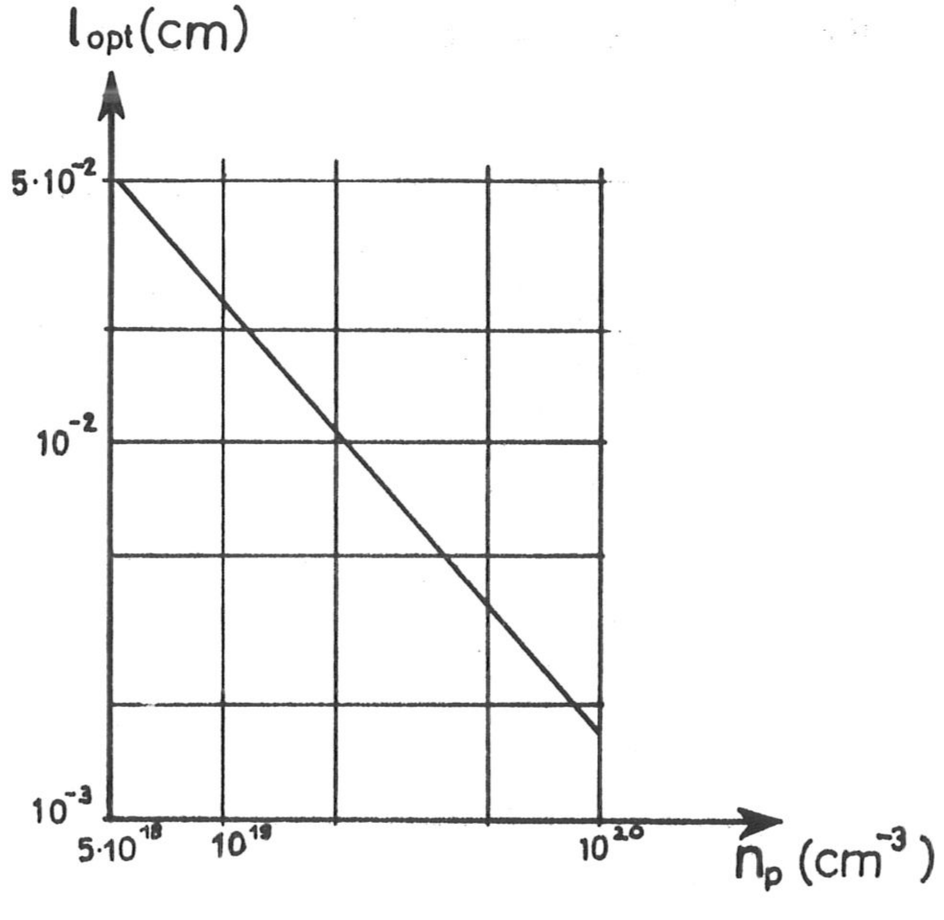


Fig. 4

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