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Linear photogalvanic effect in semiconductors in the submillimeter spectral range

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A linear photogalvanic effect has been observed in the submillimeter spectral range in p-GaAs. It has been established that in this range light absorption and the effect are related to indirect optical transitions with phonon participation. Displacement and ballistic mechanisms of the effect related to light absorption with indirect optical transitions are examined. It is shown that an anisotropic momentum distribution of minority carriers develops. The displacement current caused by hole displacement in real space for indirect transitions is calculated.

The photogalvanic effect which occurs in homogeneous crystals upon uniform irradiation and is caused by anisotropy of photo-excitation, scattering, and recombination processes in crystals lacking an inversion center has been widely studied in recent years. In crystals with T_d symmetry the effect is described by the phenomenological equation

$$j_\alpha = I\chi\,|\delta_{\alpha\beta\gamma}|\,e_\beta e_\gamma, \tag{1}$$

where I is light intensity, e is the polarization vector, and $\delta_{\alpha\beta\gamma}$ is a unit antisymmetric tensor. The effect has been studied previously in the visible and IR ranges.[1-5]

The present study is dedicated to detection and study of the linear photogalvanic effect in the submillimeter spectral range. The photocurrent studies were performed in p-GaAs.

Light absorption on free carriers in semiconductors with a degenerate valent zone is caused by direct intersubzone transitions and indirect transitions with participation of phonons and impurities. Both types of photo-excitation may lead to appearance of a linear photogalvanic current, caused by displacement[6,7] and ballistic[4,8] mechanisms.

In the previously studied case[3,4] of p-GaAs excitation by CO_2 laser radiation with wavelength $\lambda = 10.6\ \mu$ at $T > 200$ K light absorption was controlled by direct transitions between heavy and light hole subzones.

The displacement current is then related to hole displacement in real space as a result of direct optical transitions or scattering on phonons of photoexcited carriers, distributed anisotropically over momentum. The ballistic current is caused by the acquisition of a directed velocity by carriers in both direct optical transitions accompanied by absorption or emission of a single phonon[4,8] and in two-phonon relaxation of the anisotropic carrier distribution.

On transition to the sub-millimeter wavelength range a new situation develops, since the coefficient of light absorption on indirect transitions increases significantly and the ratio of the contributions of phonon and impurity mechanisms to photocarrier scattering changes.

1. OBSERVATION OF THE LINEAR PHOTOGALVANIC EFFECT IN THE SUBMILLIMETER WAVELENGTH RANGE

The effect was studied in p-GasAs (Zn) with an impurity concentration of $5\cdot10^{15}$-$3\cdot10^{17}$ cm^{-3} in the temperature range 200-500 K. The linearly polarized light source was an NH_3 laser with optical

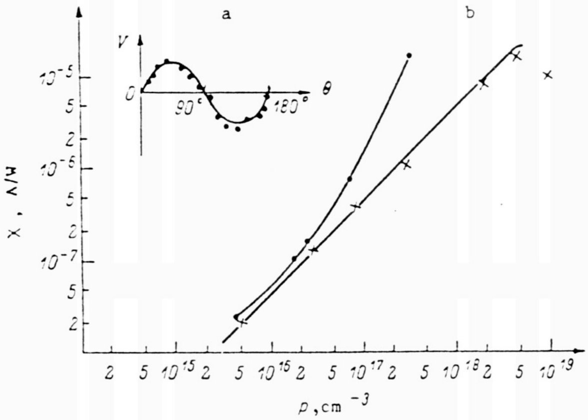

FIG. 1. a) Photogalvanic effect signal in p-GaAs at λ = 90.55 μm at T = 300 K vs angle θ; b) Photogalvanic effect constant χ vs p-GaAs hole concentration, T = 300 K. Circles, λ = 90.55 μm; crosses, λ = 10.6 μm (Ref. 4).

pumping[9,10]. The radiation wavelength was 90.55 μ, with a pulse duration of 40 nsec. The specimens were cut in the form of a thin plate, on the faces of which two ohmic contacts were placed in the $(1\bar{1}0)$ direction A signal was then observed which repeated the form of the laser pulse and was linearly dependent on light intensity in the range I < 100 kW/cm². Upon rotation of the plane of polarization relative to the direction $(1\bar{1}0)$ the observed emf depended on the angle θ between the polarization vector and the direction (110) as $\sin 2\theta$ (Fig. 1a). Rotation of the specimen about the axis $(1\bar{1}0)$ by 180° for unchanged light propagation direction led to a change in signal polarity. Thus the photocurrent behaved in accordance with phenomenological equation (1). The quantity χ which defines the current in Eq. (1) is related to the experimentally observed emf value in the following manner

$$\chi = V\sigma h \frac{Kd\,(1 - R\exp(-Kd))}{[1 - \exp(-Kd)]\,(1 - R)\,I}\,\frac{1}{\sin 2\theta}, \tag{2}$$

where σ is the conductivity, d is the specimen thickness, h is specimen width, I is the intensity of the light incident on the specimen, R is the reflection coefficient, and K is the total absorption coefficient.

2. LIGHT ABSORPTION IN p-GaAs

Light absorption in the submillimeter wavelength range at a temperature T > 200 K, where impurities are ionized, may be controlled by either direct or indirect transitions. With decrease in phonon energy the light absorption coefficient for direct transitions falls (at T = 300 K the absorption coefficient at λ = 90.55 μm is approximately four times lower[7,11] than at λ = 10.6 μm), while the absorption coefficient for indirect transitions increases. Therefore absorption on indirect transitions may play a significant role. In semiconductors with a degenerate valent zone these transitions occur with participation of phonons or impurities both within the limits of a single subzone and between subzones.

An expression for the light absorption coefficient resulting from indirect optical transitions K_{ind} was presented for semiconductors with a simple zone in Ref. 12. Consideration of degenerate valent zone structure leads to changes in this expression. In the case where absorption occurs with participation of an LO-phonon and the initial, intermediate, and final states are located in the heavy hole subzone, this expression has the form

$$K = \frac{2}{3\pi}\,\frac{e^2}{\hbar c n_\omega}\,\frac{p\,(2\pi\hbar^2)^{3/2}}{(m_1^{3/2} + m_2^{3/2})}\left(1 - \exp\left[-\frac{\hbar\omega}{k_B T}\right]\right)\frac{\Omega}{\omega}\,\frac{e^2 m_1}{\hbar^2\varepsilon^*}\,\frac{(\hbar\omega)^{-2}}{(k_B T)^{1/2}}$$
$$\times\,[\hbar(\omega + \Omega)\exp[\hbar(\omega + \Omega)/2k_B T]\,K_1(\hbar(\omega + \Omega)/2k_B T)$$
$$+\,\hbar|\omega - \Omega|\exp[\hbar|\omega - \Omega|/2k_B T]\,K_1(\hbar|\omega - \Omega|/2k_B T)]. \tag{3}$$

Here ω is the frequency of the exciting light, Ω is the optical phonon frequency, $\varepsilon^{-1} = \varepsilon_0^{-1} - \varepsilon_\infty^{-1}$, ε_0 and ε_∞ are the static and hf dielectric permittivities, n_ω is the index of refraction at frequency ω, m_1 is the mass of heavy, m_2, of light holes, and K_1 is a Macdonald function.

Aside from processes occurring within the heavy subzone, a perceptible contribution to absorption is produced by indirect transitions with participation of states in the light hole subzone. However even without their consideration at λ = 90.55 μm and T = 300 K the quantity defined by Eq. (3) is 1.5 times greater than the absorption coefficient for direct transitions.

It must be noted that the contributions to the light absorption coefficient from direct transitions and indirect transitions with phonon participation have opposite temperature dependences – growth in temperature at T > 200 K leads to increase in absorption by indirect transitions and decrease in absorption by direct transitions.

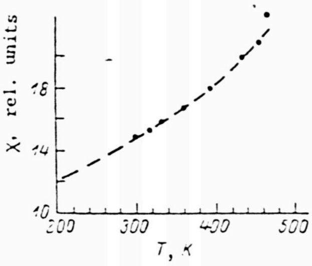

FIG. 2. Absorption coefficient in p-GaAs (λ = 90.55 μm) with $p = 5\cdot10^{15}$ cm⁻³ vs temperature. Circles, experiment; dashes, calculation by Eq. (3) with consideration of lattice absorption.

The transmission properties of p-GaAs specimens with free carrier concentrations of $5\cdot10^{15}$–$7\cdot10^{17}$ cm⁻³ at temperatures of 300-500 K were studied experimentally. The absorption coefficient values obtained at T = 300 K and λ = 90.55 μm can be described by the following dependence on carrier concentration:

$$K = S_a p + K_\ell. \tag{4}$$

where $S_a = 2\cdot10^{-15}$ cm⁻² is the intrazone light absorption section, and $K_\ell \cong 5$ cm⁻¹ is the coefficient for absorption on lattice oscillations.

The temperature dependence of the absorption coefficient is shown in Fig. 2. The increase in the absorption coefficient with temperature indicates that absorption is determined by indirect transitions. The linear growth of absorption with concentration together with its temperature dependence (Fig. 2) suggests that absorption occurs with participation of polar optical phonons, while ionized impurities do not participate. According to Ref. 7 the absorption coefficient for direct transitions at T = 300 K and λ = 90.55 μm is equal to $2\cdot10^{-16}$ p, which comprises 10% of the experimen-

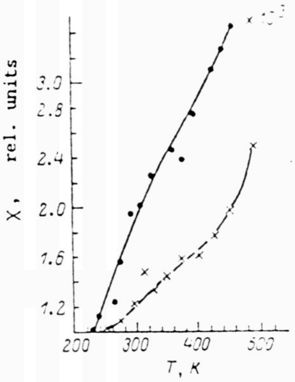

FIG. 3. Photogalvanic effect constant λ = 90.55 μm. Circles, p = $5\cdot10^{15}$ cm^{-3}; crosses p = $3\cdot10^{17}$ cm^{-3}.

tally observed value. At higher temperatures the contribution of direct transitions to absorption is smaller yet.

3. PHOTOGALVANIC EFFECT MECHANISM IN THE SUBMILLIMETER WAVELENGTH RANGE

We will first consider the contributions to the effect related to light absorption with direct optical transitions. A decrease in quantum energy leads to reduction in the energies for the initial and final carrier states participating in absorption. In the submillimeter range these values prove to be less than the energy of an optical phonon. As a result contributions to current related to appearance of asymmetry in the carrier distribution over momentum space or displacement in real space upon phonon emission disappear. The absence of these contributions leads to a change in the temperature dependence of the effect related to light absorption with direct transitions. Under these conditions the former practically coincides with the temperature dependence of the absorption coefficient so that increase in temperature leads to a decrease in the value of the photogalvanic current.

In the submillimeter spectral range aside from the indicated linear photogalvanic effect mechanisms, mechanisms involving photo-excitation with indirect transitions are possible. First we have displacement current, caused by displacement of the center of gravity of a hole wave packet for an indirect optical transition with phonon participation. This current, proportional to the first power of the carrier concentration, will be considered in the appendix. Second, we have displacement currents caused by relaxation of the anisotropic charge carrier momentum distribution which also develops for indirect transitions. In particular, as a result of optical transitions with absorption of an LO-phonon with initial, intermediate, and final states in the heavy hole subzone an anisotropic component appears in the carrier momentum distribution, proportional to $o_x o_y$,

$$\delta f^{+}_{1\mathbf{k}} = -\frac{KI}{\hbar\omega}\,\tau_{1k}\,\eta_{ind}\,o_x o_y e_x e_y, \tag{5}$$

where the degree of orientation η_{ind} is defined by the expression

$$\eta_{ind} = 6\left[\frac{D_0(\xi)}{2}t - \frac{3}{5}D_3(\xi) - \frac{7}{5}D_1(\xi) + \frac{D_2(\xi)}{2}(t + t^{-1}) + \frac{t^{-1}}{2}\left(\frac{18}{35}D_4(\xi) + \frac{2}{7}D_2(\xi) + \frac{D_0(\xi)}{5}\right)\right],$$

$$\xi = \frac{2k^2 + 2m_1(\Omega + \omega)\hbar}{2k\sqrt{2m_1(\Omega + \omega)\hbar}}, \quad t = \frac{k}{\sqrt{k^2 + 2m_1(\Omega + \omega)\hbar}}, \tag{6}$$

where $\mathbf{k}$ is the hole wave vector and D_j is a Legendre function of the second sort.

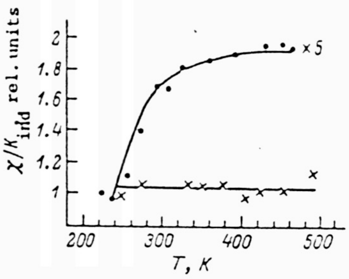

FIG. 4. Photogalvanic effect constant normalized to absorptio coefficient for indirect transitions χ/K_{ind} in p-GaAs (λ = 90.55 μm) vs temperature. Circles, p = $5\cdot10^{15}$ cm^{-3}; crosses p = $3\cdot10^{17}$ cm^{-3}.

The quantity η_{ind} for λ = 90.55 μm is 2-3 times smaller than the degree of orientation η_{dir} corresponding to the anisotropic hole distribution which develops upon direct optical transitions (η_{dir} = −3 and in contrast to η_{ind} is independent of the wave vector). However since light absorp tion due to indirect transitions dominates, the ph current related to the corresponding distribution anisotropy may exceed the current produced by anisotropy of photo-excitation with direct transitions. We stress that the carrier distribution func tion, Eq. (5), in real space a displacement photo current developes upon scattering on phonons or impurities. Its concentration dependence is related to both which scattering mechanism leads to the greater shift and to which of the scatterin mechanisms determines the effective relaxation tim of anisotropic distribution (5). If the shift and relaxation time are both determined by one and the same scattering mechanism, then the current dependence on carrier concentration is linear. If the shift is related to scattering on phonons, while the relaxation time is determined by scatter ing on ionized impurities, then the current is independent of carrier concentration. In the case where the relaxation time is determined by phono and the shift by impurities, the current depende on carrier concentration is quadratic.

Also related to anisotropy of the carrier momentum distribution which occurs upon direct transitions are ballistic contributions to the curre Single scattering of photo-excited holes, leading to a displacement current do not cause a directed velocity to develop. Its development is related to interference of processes in which either phon or impurities or both simultaneously participate.

The ballistic contributions depend on carrier concentration in a different manner, depending on the mechanism by which the mean velocity app In particular, if the relaxation time is determined by interaction with LO-phonons, then the current related to interference of phonon processes is line in concentration, while the current produced by processes with participation of phonons and ionize impurities is quadratic. A ballistic contribution may also arise as a result of interference of vario transition processes with participation of a phono and two phonons.[13]

We will consider the observed principles of the linear photogalvanic effect. Figure 1b shows the dependence of the constant χ on carrier concentration. The same figure shows the analogous dependence for excitation by light at λ = 10.6 μm (Ref. 4). It is evident that in both cases in concentration range $5\cdot10^{15}$-$3\cdot10^{16}$ cm^{-3} χ depends linearly on p, while the absolute values of χ in the 10.6 and 90.55 μm regions are similar. For a concentration $p > 3\cdot10^{16}$ cm^{-3} for the case λ = 10.6 μm as before χ is linear in p, while for λ = 90.55 μm the dependence becomes more intense, transforming to quadratic. The linear photogalvanic effect studies performed showed on increase in current with temperature (Fig. 3). This eliminates the possibility that the photocurrent is mainly related to light absorption with direct optical transitions. The fact is that for a temperature change from 200 to 500 K the observed current increases ~3 times, while the current produced by absorption on direct transitions must decrease ~6 times.

We will now analyze the experimental data for low concentrations, where the photocurrent depends linearly on carrier concentration. In this case, as follows from its temperature dependence, the linear photogalvanic effect is related to absorption with indirect optical transitions. The linear dependence of current upon concentration corresponds to mechanisms in which both carrier relaxation and the appearance of a mean velocity or mean carrier displacement are determined by scattering by optical phonons. The photocurrent is then caused by asymmetry of electron–photon or electron–phonon interaction. As experiment shows, the efficiency of processes leading to asymmetry increases with increase in temperature (Fig. 4a). This figure shows the dependence of the quantity χ, normalized to the absorption coefficient for indirect transitions, upon specimen temperature. The normalization was performed to eliminate the temperature dependence of the absorption coefficient and to clarify to what degree the processes responsible for appearance of the current depend on temperature.

We will now consider the case of high concentrations $p > 3\cdot10^{16}$ cm^{-3}, where the concentration dependence of photocurrent changes from linear to quadratic. In this case, as before, the current is related to absorption with indirect optical transitions and participation of phonons. The efficiency of the processes responsible for appearance of current is practically temperature independent (Fig. 4b). The quadratic dependence on concentration indicates that the case is realized in which the relaxation time of nonequilibrium holes is determined by scattering by optical phonons, while the displacement or development of mean carrier velocity is related to scattering by ionized impurities.

Thus, in the submillimeter spectral range the qualitative dependences indicate that the linear photogalvanic effect is related to light absorption with indirect optical transitions and participation of phonons, while impurity centers have a significant effect on its formation.

Calculation of this current, produced by various mechanisms, is unusually cumbersome and beyond the scope of the present study. The calculation of the displacement component performed here for indirect optical transitions indicated that its value for λ = 90.55 μm at T = 300 K is ~80 times greater than the experimentally observed value. It can be proposed that as in the case λ = 10.6 μm (Ref. 7), the current contributions are comparable in magnitude but have different signs. Therefore the net effect is less in value than each of its components.

We will note that in the experimental dependences at λ = 90.55 μm no linear photogalvanic effect caused by light absorption with direct transitions appears. Calculation of the two compnonents produced by asymmetry of the hole-phonon interaction, the ballistic and the displacement, using the expressions presented in Refs. 7, 8 for λ = 90.55 μm and T = 300 K gives a current value 1.5 times smaller than the experimental. Apparently the contributions related to hole-photon interaction asymmetry further reduce the value of the current.

In conclusion we will note that upon transition to lower temperatures T = 78 K, where in p-GaAs freezing of carriers to the impurity occurs, there is a change in the polarity of the linear photogalvanic effect.

In n-GaAs, as for excitation by light with λ = 10.6 μm (Ref. 14), in the p range $5\cdot10^{15}$-10^{17} cm^{-3} a signal is found which is independent of the angle θ and unrelated to the linear photogalvanic effect. Observation of this effect in n-GaAs at λ = 90.55 μm with heavier doping is difficult because of intense plasma reflection of the radiation.

APPENDIX

We will calculate the photocurrent produced by displacement of carriers in real space for indirect optical transitions.

Using perturbation theory, as in Ref. 6, it can be shown that the displacement $\mathbf{R}_{l'\mathbf{k}'l\mathbf{k}}$ of the center of gravity of the hole wave packet for an indirect transition from the state $l\mathbf{k}$ to the state $l'\mathbf{k}'$ is given by the expression

$$\mathbf{R}_{l'\mathbf{k}'l\mathbf{k}} = -(\nabla_{\mathbf{k}} + \nabla_{\mathbf{k}'})\,\Phi_{l'\mathbf{k}'l\mathbf{k}} + \Omega_{l'\mathbf{k}'} - \Omega_{l\mathbf{k}}, \qquad (A.1)$$

where $\Omega_{l\mathbf{k}}$ is the portion of the coordinate matrix element diagonal to the wave vector, $\Phi_{l'\mathbf{k}'l\mathbf{k}}$ is the phase of the composite matrix element $M_{l'\mathbf{k}'l\mathbf{k}}$, which for transitions within the limits of the heavy hole subzone has the form

$$M_{1\mathbf{k}'1\mathbf{k}} = \frac{eA_\omega}{c}\left[\frac{\mathbf{e}\hat{\mathbf{v}}_{1\mathbf{k}'1\mathbf{k}'}\hat{D}_{1\mathbf{k}'1\mathbf{k}}}{E_{1\mathbf{k}'} - E_{1\mathbf{k}} - \hbar\Omega} + \frac{\hat{D}_{1\mathbf{k}'1\mathbf{k}}\mathbf{e}\hat{\mathbf{v}}_{1\mathbf{k}1\mathbf{k}}}{-\hbar\omega}\right]. \qquad (A.2)$$

Here A_ω is the amplitude of the light wave vector-potential, $\mathbf{e}$ is the polarization vector, $\hat{\mathbf{v}}$ is the velocity operator, $\hat{D}$ is the hole–phonon interaction operator with consideration of polar and deformation scattering mechanisms, defined by Eq. (1) of Ref. 7. As a result of the displacement of Eq. (A.1) there develops a photocurrent

$$\mathbf{j} = e\sum_{l\mathbf{k},l\mathbf{k}'} W_{l'\mathbf{k}'l\mathbf{k}}\mathbf{R}_{l'\mathbf{k}'l\mathbf{k}}. \qquad (A.3)$$

where $W_{l'\mathbf{k}'l\mathbf{k}}$ is the probability of the transition $l\mathbf{k} \rightarrow l'\mathbf{k}'$.

For the current contribution related to transitions within the limits of the heavy hole branch, after summation over degenerate states and averaging over solid angles θ and θ' of the vectors $\mathbf{k}$ and $\mathbf{k}'$, we obtain

$$j = Ie\,\frac{d_0}{\sqrt{3}\,c}\,\frac{e^2\Omega N_\Omega}{\varepsilon^*}\,\frac{\hbar^2 m_1(\Omega + \omega)}{cn_\omega(\hbar\omega)^4}\int\limits_0^\infty\int\limits_0^\infty k^2dk\,k'^2dk'\,f_{1\mathbf{k}}\delta \qquad (A.4)$$
$$\times\,(E_{1\mathbf{k}} - E_{1\mathbf{k}'} - \hbar\omega - \hbar\Omega)\,(26D_4(\varphi) + 65D_2(\varphi) + 21D_0(\varphi))\,245.$$

Integration over the wave vector modulus yields a value $\chi = 4.5\cdot10^{-22}$ A·cm^3/W. The contribution of other indirect transitions is comparable to that calculated.

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Electron–hole liquid in thin semiconductor filaments

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Systems of thin semiconductor filaments a high permittivity are considered and the ground-state energy of the electron-hole liquid in such systems is calculated together with the equilibrium value of the density as a function of the filament thickness. Possible formation of an insulating electron-hole liquid is discussed.

Preparation and investigation of one-dimensional semiconductor systems is one of the most interesting problems of contemporary solid-state physics.[1] Recent technological progress has led to preparation of systems of thin semiconductor filaments in an insulating matrix such as systems of GaAs one-dimensional filaments (quantum one-dimensional conductors) in $Al_xGa_{1-x}As$ (see Refs. 2 and 3), plane superlattices (periodic modulation of surface charge density in a metal–insulator–semiconductor system) (see Ref. 4), ultrathin channels in GaAs (Ref. 5) and in silicon field-effect transistors.[6-8] However, the permittivities of the semiconductor filaments ε_1 and of the insulating matrix ε in such systems were close to are another.

We shall consider the case

$$\alpha = \varepsilon_1/\varepsilon \gg 1 \tag{1}$$

which is realized when semiconductors and semimetals are introduced into channels of insulating crystal matrices (chrysotile asbestos materials) containing crystallographically ordered systems of cavities and channels (channels of diameter 20-150 Å).[9] It was shown in Ref. 10 that the Coulomb interaction in thin semiconductor and semimetal filaments placed in an insulating medium with $\alpha \gg 1$ increases rapidly when the filament thickness is reduced.

We shall consider filaments of a diameter a satisfying

$$a_0 \ll a \ll a_1, \tag{2}$$

where a_0 is the interatomic distance and $a_1 = \varepsilon_1 \cdot \hbar^2/me^2$ is the Bohr radius of an exciton in a bulk semiconductor forming the filament (m is the reduced exciton mass). The interaction energy of charges e_1 and e_2 located within the filaments at points $z_1 = 0$, $\rho_1 = 0$ and $z_2 = z$, $\rho_2 = \rho$ (the z axis is the axis of the filament) is independent of ρ for $|z| \gg a$ and has the form

$$V(z) = \int_{-\infty}^{\infty} \frac{dk}{2\pi} \cos kz V(k). \tag{3}$$

For z satisfying the inequality

$$a \ll |z| \ll a\sqrt{\alpha \ln \alpha}, \tag{4}$$

we obtain

$$V(k) = \frac{e_1 e_2 \alpha \ln \alpha}{\varepsilon_1} \frac{1}{1 + \frac{\alpha}{2}(ak)^2 \ln \alpha}. \tag{5}$$

The potential (3) then has the form

$$V(z) = \frac{e_1 e_2}{\varepsilon_1 a} \sqrt{\frac{\alpha \ln \alpha}{2}} \left[1 - \frac{|z|}{a} \sqrt{\frac{2}{\alpha \ln \alpha}}\right]. \tag{6}$$

To be able to neglect the motion of a particle in a direction perpendicular to the filament axis, we require that the separation between the size-quantized energy levels of transverse motion $E_q \sim \hbar^2/ma^2$ is much greater than the corresponding values for motion parallel to the axis. When this condition is satisfied, all the particles occupy only the lowest quantum level and the problem of relative motion of charges becomes one-dimensional.