ing values for the depth of the craters formed under the action of the intense REB: in duraluminum, $H=4.07$ mm, in copper, $H=1.97$ mm. This agrees with the experimental results to within 25%.

The good agreement of the experimental results on hypervelocity impact and high-current REB shows that many hypervelocity-impact phenomena can be modeled with the help of a pulsed intense REB. By extrapolating the results, we can hope that upon increase in the energy of the REB to 100 kJ, and at a power density of 10^{14} W/cm^2, we can model experiments on hypervelocity impact of aluminum on aluminum at speeds up to $V\approx 50$ km/s.

In conclusion, the authors express their gratitude to S.S. Batsanov and L.I. Rudakov for valued discussions.

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Fluctuation conductivity in V_3Ge near the second critical field

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It is demonstrated by experiment that the superconducting compound V_3Ge has a fluctuating excess conductivity above the second critical point H_{c2}. The magnetic-field dependence of the excess conductivity, measured with the field perpendicular to the sample axis, agrees well with the predictions of the theory. The resistivity ρ_f to the current flow below H_{c2} is found to deviate from the results of the theory that does not take the fluctuations into account. The agreement of the estimated width of the fluctuation region and of the value of the additional conductivity with the observed region of the anomaly of ρ_f suggests that the fluctuation mechanism manifests itself also below H_{c2}.

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INTRODUCTION

It is known[1] that an excess conductivity (paraconductivity) due to fluctuation pairing of the electrons takes place above the superconducting-transition point. In the absence of a magnetic field, i.e., above $T_c(0)$, this effect has been sufficiently well investigated, especially in films.[1] In the presence of a magnetic field, the paraconductivity of bulk samples and films has not been sufficiently investigated and the experimental data[2-4] do not agree fully with the theoretical results.[1,5] At the same time, paraconductivity above the second critical field H_{c2} is of interest because in homogeneous samples the electric resistivity in the H_{c2} region (disregarding the fluctuations) is finite on both sides of the transition and, according to the prevailing theories,[6] it is close to the resistivity in the normal state below H_{c2}. This raises the question of the extent to which the resistivity decreases above H_{c2} and whether it varies nomonotonically[7] or monotonically[8] in homogeneous samples on going below H_{c2}.

Allowance for the fluctuations above H_{c2} leads in the linear approximation[5] to the following dependence of the excess conductivity $\Delta\sigma$ on the magnetic field:

$$\Delta\sigma=\frac{\pi}{2\sqrt{2}}\frac{e^2}{\hbar}[\xi(0)]^{-1}F(t,h), \tag{1}$$

where $\xi(0)$ is the coherence length and $F(t,h)$ is a universal (independent of the material parameters) function of the relative temperature $t=T/T_c(0)$ and the relative field $h=H/H_{c2}$. Below H_{c2} the excess conductivity has the same behavior[9] if the current is perpendicular to the field, and differs only by a factor $\ln[L/\xi(T)]$,

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where L is the sample dimension in the direction perpendicular to the magnetic field and to the current. The excess conductivity of a bulky type-II superconductor with transverse dimensions of the order of 1 mm and with $\xi = 50$ Å is thus expected to exceed the value of $\Delta\sigma$ at $H > H_{c2}$ by an order of magnitude.

The paraconductivity due to the fluctuations increases with increasing H_{c2}. The reason is that the size of an individual fluctuation, proportional to ξ, decreases with increasing H_{c2}, and the appearance of fluctuations becomes more probable. An experimental study of the effect of the fluctuations on the conductivity of superconductors with small correlation lengths ($\xi = 30$–50 Å) is therefore much simpler than experiments with type-I superconductors ($\xi = 500$ Å), where the broadening of the transition is extremely small.

Since the conductivity is affected, besides by the fluctuations, also by the magnetoresistance and by the surface superconductivity, a sample is needed in which these effects are negligibly small or can be taken into account. In addition, it is desirable to use in the experiment a material with high residual resistivity, since it is easier to observe a small excess conductivity against the background of a small basic conductivity.

All these requirements, as will be shown below, are met by V_3Ge, which is a type-II superconductor with A-15 structure and with a critical temperature 6.1 K. At a temperature below 1500 °C its homogeneity region (which is quite narrow, of width 0.2–0.3%) is shifted towards the vanadium, does not include stoichiometry,[10] and has consequently a large residual resistivity. In its chemical and metallurgical properties this intermetallide is similar to V_3Si, so that its single crystals can be grown by the methods developed for the latter.

We present here the results of the measurements of the resistivity of a number of V_3Ge samples at 4.2 K in fields both stronger and weaker than H_{c2}. Above H_{c2} the results are in good agreement with the theoretical calculations of the fluctuation conductivity. Below H_{c2} one observes a substantial decrease of the resistance compared with the predictions of the theory[6] that does not take the fluctuations into account. This behavior can also be explained within the framework of the fluctuation mechanism.

PROCEDURE

We used for the measurements single-crystal and polycrystalline V_3Ge samples cut by the electric-spark method from an ingot obtained by zone melting in an argon atmosphere. The outer layer deformed by the cutting was removed by etching for 10–20 minutes in a mixture of equal parts of HF and HNO_3. To estimate the effect of the surface superconductivity, the samples were cut to have either a rectangular (side ratio 1 : 5) or a trapezoidal cross section. The cross-section area was 0.2–1.5 mm^2. Some of the samples were subjected to homogeneizing annealing at 1400 °C for 8 hours in a V_3Ge container.

A magnetic field up to 60 kOe was produced by a superconducting solenoid and was measured with relative error 0.05%. The resistivity was measured by the usual four-contact method with mutually perpendicular orientation of the magnetic field and of the measuring current flowing along the long axis of the sample, with a relative error $(1-2)\times 10^{-4}$. The ±10% error in the measurement of the resistivity was due to the inaccurate determination of the geometric dimensions of the sample. The density of the current through the sample was varied in the range 0.01–90 A/cm^2. The measurements were made with the magnetic field directed in the plane of either the board or the narrow face of the sample.

TABLE I.

Sample No.	ρ_{res}, μΩ · cm	ρ_{300K}/ρ_{res}	H_{c2}(4.2K), kOe	$\Delta H_{c2}/H_{c2}$, %	$\xi(0)$, Å	α	σ_0, (Ω · cm)$^{-1}$
6*	–	–	45.6	0.2	48	–	560
7	54	1.63	43.2	0.5	48	0.91	560
9	66	1.37	44.7	2.7	48	1.07	560
11	30	2.56	27.3	4.8	61	0.93	440
14	28.5	3.06	26.1	2.2	61	0.98	440
15	29.5	3.05	26.1	15	61	1.07	440
20	28.4	2.85	26.7	16	61	1.07	440

Note. $\xi(0) = (\Phi_0/2\pi H_{c2}(t))^{1/2}$, $(1-t)^{1/2}$, $\alpha = \Delta\delta\cdot\xi(0)/\overline{\Delta\delta\cdot\xi(0)}$ — deviation of the product of the conductivity above H_{c2} and the correlation length from the same value averaged over the entire sample.

*Sample in a shell; ρ_{res} and ρ_{300K}/ρ_{res} were not determined.

For all samples, H_{c2} was taken to be the field corresponding to the resistivity midpoint at minimum measuring-current density. The transition width ΔH_{c2} was defined as the difference between the fields corresponding to $0.9\rho_n$ and $0.1\rho_n$ (ρ_n is the resistivity in the normal state). The parameters of some of the samples are listed in Table I.

Typical dependences of the critical current j_c on h are shown in Fig. 1. All samples reveal the presence of a peak effect near $h = 1$. The peak effect is perceptible in samples with $H_{c2} \approx 27$ kOe and weak in samples with $H_{c2} \approx 44$ kOe. The critical-current density in average fields $h = 0.3$–0.8 is minimal for sample No. 6. This sample differs from the other in that it was heat treated without a container. Owing to the preferred evaporation of the germanium, the result was a two-phase structure, the shell being a solution of germainum in vanadium and the core V_3Ge,

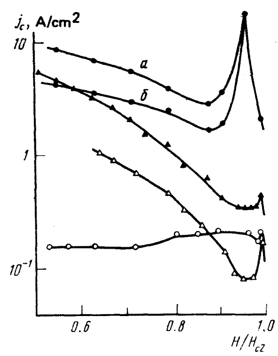

FIG. 1. Typical plots of $j_c(h)$ of the investigated samples: ○) sample No. 6, ▲) No. 7, △) no. 9; ●) No. 20.

i.e., the conditions on the boundary were altered: the superconductor–metal contact. The low critical current of this sample seems to attest to a dominant contribution of pinning in the surface layers of the other samples. The decisive role of pinning follows also from the results of the measurement of $j_c(h)$ at various sample orientations in the magnetic field: when H is parallel to the long face (Fig. 1, sample 20a) j_c is larger than when H is parallel to the short faces (b).

RESULTS AND DISCUSSION

1. Dependence of conductivity on the magnetic field at $H > H_{c2}$

Typical results of the measurements of the excess conductivity above H_{c2} for several samples with different values of H_{c2} and with different transition widths are shown in Fig. 2. To facilitate the check against the theory and the comparison of the data, the relative coordinates $H/H_{c2} - 1$ and $\Delta\sigma/\sigma_0$ are used, where

$$\sigma_0 = \frac{\pi}{2\sqrt{2}}\frac{e^2}{\hbar}[\xi(0)]^{-1}, \quad \Delta\sigma = \sigma_{\mathrm{meas}}(H) - \sigma_n,$$

σ_n is the conductivity in the normal state. Since σ_n cannot be measured directly, we assumed that $\sigma_n = 0.9996\sigma(2H_{c2})$. This choice fits the experimental values of $\Delta\sigma/\sigma_0$ at the maximum filled to the theoretical plot, which is also shown in Fig. 2. The results of Fig, 2 demonstrate the existence of a universal dependence of $\Delta\sigma/\sigma_0$ on H/H_{c2}. The upward deviations from this dependence for various samples occur at values of $H/H_{c2} - 1$ that are close to the width of the transition, and are due to the influence of inhomogeneities. In stronger fields the effect of the inhomogeneities vanishes rapidly, in agreement withe the quantitative estimates. Thus, if the different sections of a sample have values of H_{c2} in the interval from $H_{c2}^{\min}$ to $H_{c2}^{\max}$, then the reduced correction to the additional conductivity on account of the inhomogeneity of the sample, is

$$\frac{\Delta\sigma(H) - \Delta\sigma_{\mathrm{id}}(H; H_{c2}^{\mathrm{av}})}{\Delta\sigma_{\mathrm{id}}(H; H_{c2}^{\mathrm{cp}})} = \frac{\delta}{\gamma}\ln\left(\frac{2\delta+\gamma}{2\delta-\gamma}\right) - 1,$$

where

$$\delta = H/H_{c2}^{\mathrm{av}} - 1, \quad \gamma = (H_{c2}^{\max} - H_{c2}^{\min})/H_{c2}^{\mathrm{av}},$$

$H_{c2}^{\min} < H_{c2}^{\mathrm{av}} < H_c^{\max}$; $\Delta\sigma_{id}(H; H_{c2})$ is the dependence of the additional conductivity on the magnetic field of a homogeneous sample with $H_{c2} = H_{c2}^{\mathrm{av}}$.

The field dependence of $\Delta\sigma/\sigma_0$ of samples whose surface was mechanically polished differs substantially from the universal dependence (Fig. 2). This is apparently due to the increase of H_{c2} in the surface layer on account of case hardening. Chemical treatment after the mechanical polishing lowers the excess conductivity, and the $\Delta\sigma/\sigma_0$ dependence becomes completely analogous to that for the other samples. At large measurement currents ($j \approx 40$ A/cm^2) the excess conductivity decreases (Fig. 3), owing to the overheating of the sample and the ensuing decrease of H_{c2}. This conclusion is confirmed by the fact that $\Delta\sigma(H)/\sigma_0$ plotted for the smaller H_{c2} fits the universal plot. The overheating is also confirmed by estimates of the heat balance.

The observed $\Delta\sigma(H)$ dependence is not connected with magnetoresistance. Resistance measurements at 78 K in the employed field interval have shown the resistance to be constant within 1×10^{-4} [i.e., at 78 K; $\sigma(H) - \sigma_0 < 3\times10^{-3}\sigma_0$]. The low value of the magnetoresistance agrees with the large resistivity. Since our samples had $\rho_{78\,\mathrm{K}}/\rho_{\mathrm{res}} \approx 1.1$, the magnetoresistance at 4.2 K was negligibly small. The surface conductivity likewise does not make a noticeable contribution to the observed value. This is proved by the following: the $\Delta\sigma(H)$ plots have no singularities at $H = H_{c3} = 1.69H_{c2}$; at current densities that produce no overheating, $\Delta\sigma(H)$ is independent of the current; $\Delta\sigma(H)$ does not change when the sample orientation in the magnetic field is changed; the functional form of $\Delta\sigma(H)$ for a sample in a normal-metal shell (No. 6) is identical with that shown in Fig. 2 (in view of the large, ~100%, error in the determination of the cross-section area of this sample, no numerical values were determined).

Comparing our data with the measurements of Hake,[2] we note that with σ_n slightly modified his results agree fully with our present data. Thus, the experimental data attest to the existence of a single $\Delta\sigma(h)/\sigma_0$ dependence for different type-II superconductors.

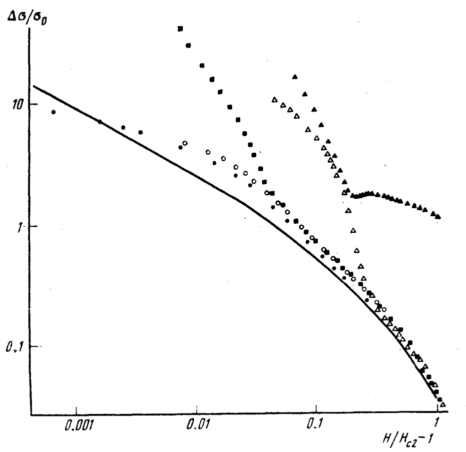

FIG. 2. Excess conductivity vs. field. Lower curve—theoretical plot of $\Delta\delta_{\mathrm{tot}}/\delta_0 = F_{\mathrm{tot}}(t,h)$. Points—experiment: ▲) mechanically polished sample, ●) sample No. 7, ■) No. 20, ○) No. 9, △) No. 15.

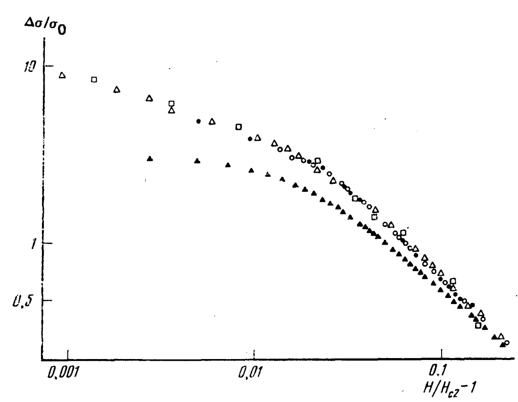

FIG. 3. Effect of overheating on $\Delta\sigma/\sigma_0$ above H_{c2}. Measuring current (A/cm^2): □) 0.4; △) 1.9; ●) 4; ▲) 40, ○) data for j = 40 A/cm^2 recalculated for a decreased value of H_{c2}.

As follows from the theory,[5] the additional conductivity is a sum of two contributions:

$$\Delta\sigma_{tot}/\sigma_0=\Delta\sigma_{A-L}/\sigma_0+\Delta\sigma_{M-T}/\sigma_0 \qquad (2)$$

($\Delta\sigma_{A-L}$ is a contribution of the Aslamazov-Larkin type and $\Delta\sigma_{M-T}$ is a contribution of the Maki-Thompson type), with $\Delta\sigma_{M-T}$ decreasing with increasing efficiency of electron scattering. For each of these contribution, universal relations $\Delta\sigma_i/\sigma_0=F_i(t,h)$ were obtained in Ref. 5 in the linear approximation. The computer-calculated $F_i(t,h)$ for our conditions ($t=0.692$) are shown in Figs. 2 and 4.

Following Gruenberg's results,[7] we can estimate that the linear approximation is valid at

$$\frac{H}{H_{c2}}-1\gg\left[\pi^2\sqrt{2}\frac{kT}{\xi^3(T)H_{cm}^2}\right]^{2/3}=0.04 \qquad (3)$$

(we used the value $H_{cm}=1.3$ kOe). In weaker fields allowance for the next terms of the expansion of the free energy in the order parameter should decrease the additional conductivity. Recognizing that there are no fit parameters in the theory, the agreement between the theoretical and experimental results (Fig. 2) in the field region where the linear approximation is valid should be regarded as satisfactory. As for the discrepancy between the experimental values and the theory in weak fields, $H/H_{c2}-1=0.01$, we note the following: In the theory H_{c2} is taken to be the field at which a nonzero solution of the Ginzberg-Landau equations appears (the fluctuations are disregarded). We, however, took H_{c2} to be the field in which the critical current vanishes. It is possible that near H_{c2}, where the excess conductivity depends strongly on $H/H_{c2}-1$, the discrepancy between the experimental and theoretical values is due just to the different definitions of H_{c2}. In addition, the analysis in Ref. 5 neglects the contribution of the Pauli paramagnetism, and this can lower the theoretical values of H_{c2}. A 2% shift of H_{c2} results in better agreement between experiment and theory (Fig. 4) at medium field. In fields close to H_{c2}, the experimental curve lies in this case, as expected, below the result of the linear approximation.

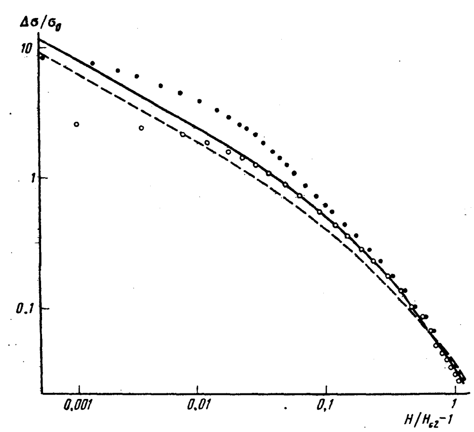

FIG. 4. Comparison of experimental data with theory: •) excess conductivity averaged over all samples, ○) the same with the value of H_{c2} shifted 2%; solid line—$\Delta\sigma_{tot}/\sigma_0=\Delta\sigma_{A-L}+\Delta\sigma_{M-T}$, dashed—$\Delta\sigma_{A-L}/\sigma_0$.

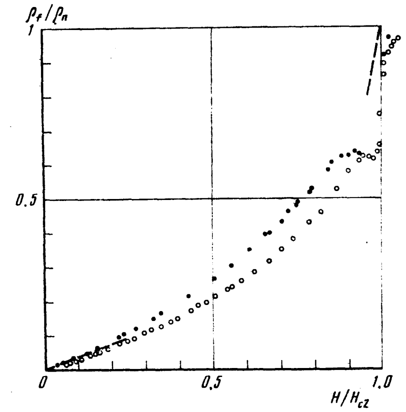

FIG. 5. Dependence of the resistivity to current flow on the magnetic field: ○) sample No 7, •) sample No. 20. Dashed lines—$\rho_f(h)$ without allowance for fluctuations in paramagnetic scattering.[6]

2. Resistivity $\rho_f(h)$ to current flow below H_{c2}

Examples of the measured $\rho_f(h)$ are shown in Fig. 5. The dashed lines are the theoretically predicted plots[6] in the limit of strong and weak fields, obtained without allowance for the fluctuations. At $h<0.8$ the samples form two groups with respect to the $\rho_f(h)$ dependence, with $H_{c2}(4.2\text{ K})=27$ kOe (sample No. 20, Fig. 5), and with $H_{c2}(4.2\text{ K})=44$ kOe (sample No. 7). Samples of the first group have ρ_f/ρ_n 1.27 times larger than the samples of the second group, and this ratio does not depend on the field. Near H_{c2} the measured ρ_f of all the samples are markedly lower than the theoretical results of Ref. 6, where no account is taken of the fluctuations. Singularities of $\rho_f(h)$ near H_{c2} (a step or even a minimum) were observed in a number of studies.[6,11] They were attributed to the influence of inhomogeneities (pinning), and particularly to the peak effect.[6] We note that arguments favoring the presence of strong nonlinearities of the current voltage characteristics (CVC) in the region of the $j_c(h)$ peak have been published,[12] but we know of no clear-cut connection between the slope of the linear section (which determines ρ_f) and the peak effect. For our samples, j_c at the peak had a range of two orders of magnitude, and for some of them the peak effect was weak (see Fig. 1), but anomalies of ρ_f near H_{c2} were always present. The linear section for samples with small j_c extended to currents 25 times larger than j_c.

It should be noted that at $h=1\pm0.02$ the CVC are nonlinear at the minimal densities of the measuring current, and have a smaller slope than on the linear section. We do not know at present whether this shape of the CVC is due to inhomogeneity of the samples (the scatter of H_{c2} over the length, pinning) or to the possible dependence of the excess conductivity on the electric field.[1] If the second assumption is valid, then the data of Fig. 5 at $h=1\pm0.02$ are overestimated and $f(h)$ can have a more pronounced minimum in this field region.

Allowance for the fluctuation may possibly explain the anomaly of $\rho_f(h)$ near H_{c2}. It follows from the foregoing that at $h-1=0.04$ both experiment and theory yield at the limit of applicability of the linear approximation an additional conductivity $\Delta\sigma = 800\ \Omega^{-1}\,\mathrm{cm}^{-1}$, which amounts to 4% of the conductivity σ_n in the normal state. Using the result of Maki and Takayama,[9] that below H_{c2} the addition to the conductivity differs by a factor $\ln[L/\xi(T)]$, we obtain at $1-h=0.04$ the value $\Delta\sigma = 0.4\sigma_n$, i.e., the fluctuations should cause ρ_f to decrease to $0.7\rho_n$, in agreement with the experimental data.

It is useful to estimate the range of fields below H_{c2} in which fluctuations can occur. It is shown in Ref. 13 that the temperature range of the fluctuation region (the region where the fluctuations are large enough for their interaction to be taken into account) is

$$\frac{\Delta T}{T_c(H)} \approx 7\left(\frac{k_B}{8\pi\xi(0)^3\Delta C}\right)^{2/3}\left(t\frac{dh_{c2}}{dt}\right)^{1/3} h_{c2}^{2/3} \quad (4)$$

[$h_{c2} = H_{c2}(t)/H_{c2}(0)$ and ΔC is the discontinuity of the heat capacity in the transition]. Substituting the parameters of V_3Ge and using for the estimate the heat-capacity discontinuity of $Ti_{84}Mo_{16}$ (Ref. 14), $\Delta C = 3\ \mathrm{mJ/cm^3\cdot K}$, we obtain $\Delta T/T_c(H) = 5\%$, or in terms of the magnetic field

$$\frac{\Delta H_{c2}}{H_{c2}(T)} = 2\frac{t^2}{h_{c2}}\frac{\Delta T}{T_c(H)} = 10\%, \quad (a)$$

which is also close to the experimentally observed width of the $\rho_f(h)$ anomaly.

Estimates of the additional conductivity and of the width of the fluctuation region thus allow us to attribute the anomalies of $\rho_f(h)$ as $h \to 1$ to fluctuations.

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Self-consistent account of exchange-correlation effects in an electron gas

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A new approximation is obtained for the local-field correction $G(\mathbf{q},\omega)$ to the permittivity $\varepsilon(\mathbf{q},\omega)$ of a homogeneous interacting electron gas. The starting point is the exact equation derived by one of us [Gorobchenko, Sov. Phys. JETP **50**, 603 (1979)] as well as an estimate of the statistical expectation values of the second-quantization operators, obtained by the technique of the coupled equations of motion for the equal-time Green's functions. The result obtained for $G(\mathbf{q},\omega)$ is compared with other known approximations. The results of calculation of the static correction $G(\mathbf{q},0)$ for the local field and of the static structure factor $S(\mathbf{q})$ are presented.

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1. INTRODUCTION

One of the central problems of the theory of simple metals is allowance for the long-range Coulomb interaction between the conduction electrons. This problem is treated as a rule within the framework of the interacting-electron-gas model against the background of a uniformly distributed positive charge.[1] It is known that practically all the physical characteristics of such a model system are expressed in terms of its permittivity $\varepsilon(\mathbf{q},\omega)$, which is customarily expressed in the form

$$\varepsilon(\mathbf{q},\omega) = 1 + \frac{Q_0(\mathbf{q},\omega)}{1-G(\mathbf{q},\omega)Q_0(\mathbf{q},\omega)}, \quad (1)$$

where $Q_0(\mathbf{q},\omega) = -v(\mathbf{q})\chi_0(\mathbf{q},\omega)$, $v(\mathbf{q}) = 4\pi e^2/q^2\Omega$ is the Fourier component of the Coulomb potential,

