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MAGNETIC FIELD DEPENDENCE OF JOSEPHSON MEDIUM CRITICAL CURRENT

The effect of a strong magnetic field H and high pressure on the Josephson junction critical current I_c and hysteresis I_c vs H is considered. It is shown that if Abrikosov vortices in the contact's superconducting electrodes are rigidly pinned, the $I_c(H)$ value strongly depends on the gradient of the vortex density, and the I_c vs H dependence has a double-step character. The first drop in I_c is for $\mu_0 H \gg \Phi_0/S_0$ ($S_0 \cong D^2$ ($\lambda_j \gg D$) or $S_0 \cong 2\lambda W$ ($W < \lambda_j$): this is followed by a plateau regime at magnetic fields $H_p \ll H \ll H_{j2} = \Phi_0/(\mu_0 W t)$. The second drop in $I_c(H)$ occurs at high enough fields $H \gg H_{j2}$. Here D is the grain diameter, W is the contact width, t is the distance between the granules (the thickness of the contact), λ, λ_j are the London and the Josephson penetration depths into the granules and intergranular space, respectively, $H_p \approx (D/2) j_{cg}$ is the field at which vortices reach the grains center.

1. Introduction

Bulk samples of high-Tc superconductors usually represent a system of superconducting grains coupled by Josephson weak links. In these samples we have in fact a collection of type-II superconductivity in grains and a low-field Josephson weak links between the grains (the Josephson medium). It is known that the magnetic field H considerably influences the critical current Jc of Josephson medium at fields $\mu_0 H \gg B_0 \cong \Phi_0/S_0$, where Φ_0 is the magnetic flux quantum and the «quantization cell» $S_0 \cong D^2 (\lambda_j \gg D)$; $S_0 \cong 2\lambda W$ ($W < \lambda_j < D$); D is the grain diameter, W is the contact width, λ, λ_j are the London and the Josephson penetration depths into the granules and intergranular space, respectively [1]. The strong J_c— H dependence weakens if Josephson critical current density is spatially inhomogeneous in the intergranular contacts [2]. In that case the S_0 value is reduced to $S_0 \cong 2\lambda r$, where r is the correlation radius of the spatial fluctuations of the Josephson critical current. But in this case the current J_c sensitivity to high H value is still large.

The situation changes considerably if Abrikosov vortices have entered in to the granules. The current of Abrikosov vortices reduces the surface current of the granules and hence changes the sensitivity of I_c of the contacts to an external field H. The main purpose of this paper is to show that, for $H \gg H_{c1}$ critical current of

Josephson contacts $I_c(H)$ in parallel fields H is associated with the reversible M_{eq} and irreversible M_{ir} portions of the granular magnetization $M(H)$. As a result the critical current of metal ceramic $J_c \sim I_c$ depends on magnetic history of the sample.

2. Physical mechanism of high field influence on Josephon contacts

The influence of a high field on the Josephson contact is related with the fact that the fields induce the screening surface current j_s within contact electrodes. This leads to the change in a phase difference $\varphi(X)$ across the junction with the rate

$$q = d\varphi/dx = (4\pi\lambda^2\mu_0/\Phi_0)\cdot dH/dy = (4\pi\lambda^2\mu_0/\Phi_0)\cdot j_s, \qquad (1)$$

where direction X is perpendicular to the external field $H = H_z$ and coordinate Y is normal to the contact surface. For the small-sized contacts ($W <$ the Josephson depth λ_j) the critical current I_c is given by the total relation [2]

$$I_c^2 = W^2 \int_0^w dx_1 \int_0^w dx_2 j_c(x_1) j_c(x_2) \exp\{i(\varphi(x_1) - \varphi(x_2))\}, \qquad (2)$$

where $j_c(x)$ is the Josephson critical current density within the plane of the contact which in general depends on the coordinate x. In the field range $B \gg \Phi_0/\lambda_j^2$ the phase difference $\varphi_1(x) - \varphi_2(x)$ can be approximated by

$$\varphi(x_1) - \varphi(x_2) \cong (d\varphi/dx)(x_1 - x_2) \equiv q(x_1 - x_2). \qquad (3)$$

Therefore according to (1—3) critical current I_c of small — sized Josephson contacts is a function of the surface current $j_s(H)$ induced by external field H within electrodes of the contact. If there are no Abrikosov vortices in granules, then $q = d\varphi/dx \sim j_s = dH/dy = H/\lambda$. After the Abrikosov vortices have entered the granules, $q \sim dH/dy \sim j_s$. Here the j_s value is not proportional to the external field H. At large fields $H \gg H_{c1}$, where $H_{c1} \cong \Phi_0/(4\pi\lambda^2\mu_0) \times \ln(\lambda/\xi)$ is the lower critical magnetic field of the grains, the magnitude of the surface screening current j_s in granules is determined by its equilibrium component j_{sm}, connected with the reversible granule magnetization M_{eq}, $j_{sm} \cong -M_{eq}/(\mu_0\lambda)$ and the irreversible one, j_{cg}, determined by the magnetic flux pinning in the vicinity of the granule surface. In most applications of the critical-state model the equilibrium (or reversible) magnetization M_{eq} is not included. This is useful approximation for the type-II superconductors with very high current densities. On the other hand, the equilibrium magnetization cannot be neglected when the irreversible magnetization becomes comparable to the reversible portion, as in the case of metal oxides [3].

The sign of j_{cg} depends on the magnetic history of the sample

$$J_s(H) \cong J_{cm}(H) \pm I_{cg}(H). \qquad (4)$$

Here the (+) sign corresponds to the external magnetic field increasing, and the (—) sign corresponds to its decrease. Hence, according to (1—4) the Josephson critical current should be given by

$$I_c(H) \equiv I_c(q(H)), \quad q(H) \approx (2\pi\mu_0/\Phi_0)\{2\lambda^2 |j_s| + tH\}, \qquad (5)$$

Here we take into account the magnetic flux $\Phi = \mu_0 H \cdot t \cdot W$ in the intergranular space, t is the distance between the granules (if there are no vortiices $j_s = H/\lambda$ and the expression in $\{\cdot\}$ brackets takes the usual form $\{\cdot\} = (2\lambda + t)H$ [2]). In (4) $j_{cg} \approx 2f\Delta M/(\mu_0 D)$, $j_{sm} \approx |M_{eq}|/(\lambda\mu_0)$, $M_{eq} = (M_+(H) + M_-(H))/2$, D is the mean diameter of granules; M_+, M_- are values of the experimental magnetization in the increasing (+) and decreasing (—) fields, $\Delta M = M_+ - M_-$, the constant $f \sim 1$. At $\Phi_0/(tW\mu_0) \gg H \gg H_{c1}$ value $q \approx$ ≈constant (H) and as a result the critical current of a Josephson contact looses its «usual» sensitivity to the magnetic field. Abrikosov vortices reduce the screening current density at the surface of the granules, thus stabilizing the critical current of Josephson contacts and therefore stabilizing the transport critical current density of ceramics [4].

Several authors, for instance [5—9], have shown experimentally that in granular high-Tc superconductors the critical current density J_c is hysteretic in an applied magnetic field. The J_c is always smaller in increasing field than indecreasing one, and this hysteresis can be observed even in high fields up to 27T. Evetts and Glowacki [5] explained the hysteresis of J_c by taking into account the effect of self-fields produced by the intergrain currents: the effective magnetic field is different for the process of decreasing and increasing H. As a result, J_c is hysteretic with cycle in H. Our results show that hysteresis of J_c^s can exist even if the magnetic field value between the grains was not changed. Aomine [9] proposed a different model, which is based on the hysteretic intragrain current due to the effect of the edge pinning at a grain boundary. In this case, a part of intragrain current goes trhough the weakly linked grain boundary and effects the transport currents.

According to our model [4] the hysteresis $J_c \sim I_c/a_0^2$ is due to the dependence of the Josephson critical current I_c on the granular surface current $j_s = j_{sm} \pm j_{cg}$ value. Here a_0 is the percolation length of a typical superconducting loop (the diameter of the percolation net) in metal ceramics. The sign of the j_{cg} depends on the magnetic history of the sample whereas the sigh of the reversible part j_{sm} is given by the direction of external field H. If the magnetic field H is increased then the vortex density at the center of the granules is smaller than that on its surface and j_{cg} has the $(+)$ sign. When the external field decreases monotonically, the vortex density at the granular boundaries is smaller than that in the center and current j_{cg} changes its sign. Therefore the irreversible effects due to the magnetic flux trapped into the granules result in usually observed [5—9] critical current hysteresis in metal ceramics.

4. Pressure effects on Josephson media current transfer

We shall show now that pressure allows to determine the Josephson contact existence in the percolation parts of the sample [10, 11]. The critical current of the Josephson contacts is given by

$$I_c \approx C\,(1 - T/T_c)^n \exp(-\zeta), \qquad (6)$$

where for SIS contacts $\zeta = t\sqrt{U}$ and for SNS contacts $\zeta = t/\xi_N$, $1 \leqslant n \leqslant 2$. Here S is the superconductor, I is the insulator, N is the normal metal; t is the thickness of the I (N) layer respectively, U is the potential barrier height, ξ_N is the coherence length in N layer). The parameter C depends on the pressure P over parameters N (0) and D, where N (0) is the electron density of states at the Fermi level, $D = (1/3)V_F l$ is the electron diffusion coefficient (the conductivity $\sigma_N \sim N(0)D$). According to (6) the pressure dependence of the Josephson critical current is given by the relation

$$d\ln I_c/dP = d\ln C/dP + \{n/(T_c - T)\}dT_c/dP - \zeta d\ln(\zeta/dP). \qquad (7)$$

Here the «Josephson part» with ζ is dominated if $\zeta \gg 1$. For the superconducting short-circuited contacts and the usual pinning mechanism the parameter $\zeta \simeq 0$ and derivative dI_c/dP are given by the derivatives dT_c/dP, $d\ln N(0)/dP$, and $d\ln D/dP$ because the change in the parameters ξ, B_c, B_{c2} and σ_N defining a pinning magnitude with the pressure are

$$d\ln \sigma_N/dP = d\ln N(0)/dP + d\ln(D)\, dP,$$

$$d\ln B_c/dP = (T_c - T)^{-1} dT_c/dP + (1/2)\, d\ln N(0)/dP.$$

$$d\ln B_{c2}/dP = (T_c - T)^{-1}\, dT_c/dP - d\ln(D)/dP.$$

For an isotopic ceramics the critical current density $J_c \approx I_c/a_0^2$. If there are no Josephson contacts, the main contribution to the $dJ_c/dP \sim dI_c/dP$ (7) is given by the change in T_c value so far as

$$d\ln \sigma_N/dP \sim (d\ln N(0)/dP,\ d\ln(D)/dP) \ll d\ln T_c/dP.$$

The pressure experiments [10—11] have shown that $\zeta \gg 1$ even in high magnetic fields. So the main dissipation-free transport current of metal ceramics flows over the structure of the weak-link Josephson contacts. In the field region up to 0.5 kOe one can try to explain this in terms of small quantization cells

S_0 produced by the spatial fluctuations of the Josephson current in weak links. In the above we have shown that the critical current stability of the Josephson granular media for $H \gg H_{c1}$ can also be associated with the existence of the Abrikosov vortex structure in the granules.

But in such case the critical current hysteresis in high magnetic fields is also to be associated with the Josephson contacts. To check this assumption an experimental investigation of the pressure effect on the hysteresis loop of the critical current J_c has been carried out [11]. As expected, there was significant increase in the hysteresis loop $J_c(P)$ with pressure, but in relative units $[(J_c(H, P)/J_c(0, P)]$ there was practically no pressure effect. These experimental facts completely agree with the theoretical concept discussed in the previous section.

5. The model calculation

In the general case the surface current j_s value can be obtained from the Maxwell equation $j_s = dH/dy$. For simplicity, we consider the contact of two infinite superconducting slabs having thickness $2L$, in a parallel magnetic field $H = H_z$, Y — axis is normal to the surface of the junction (a surface YZ), $y = 0$ is the center of superconducting slab. A suitable boundary value of induction B $(y = \pm L)$ is B_{eq}, the magnetic induction in reversible type-II material is in equilibrium with an applied field H, which is given by [12, 13]

$$B_{eq} \cong \mu_0 H + M_{eq}, \tag{8}$$

where M_{eq} is the equilibrium magnetization. The expression for the total intergranular field $H(y)$ is

$$H(y) = H_m + \Sigma_v + \Sigma_a. \tag{9}$$

Here H_m is the diamagnetic part of intragranular field H which was obtained for the boundary condition (8) that on the surface of the granules $(y = \pm L)$ the induction $B(L)$ and external field $H(L)$ are in equilibrium; Σ_v, Σ_a are the sums of the magnetic fields $h(x, y)$ of the single Abrikosov vortex,

$$h(x, y) = \Phi_0/(2\pi\mu_0\lambda^2) K_0(r/\lambda), \tag{10}$$

and their mirror image parts, respectively, $r = (x^2 + y^2)^{1/2}$, K_0 is the second order modified Bessel function. From formulae (8—10) we find the basic relation for the intragranular magnetic field H

$$\psi(y) = \{\psi(0) - \int_0^L dy' n(y') \,\mathrm{sh}(y' - L)\} \,\mathrm{ch}(y)/\mathrm{ch}(L) + \\ + \int_0^y dy' n(y') \,\mathrm{sh}(y' - y). \tag{11}$$

Here, $y = y/\lambda$, $L = L/\lambda$, $\psi(y) = \mu_0 H(y)/\Phi_0$, $\mathrm{sh}(x) = \sinh(x)$. $\mathrm{ch}(x) \equiv \cosh(x)$, $n(y)$ is the concentration of the Abrikosov vortices (the Y — direction is normal to the external field H). The current $J_s = dH/dy$ value for large granules $(L, W \gg \lambda)$ and within the interval $H_p < H_+ < H_m$ and $0 < H_- < H_m - H_p$ has the simplest form (4) (here $H_p = j_{cg} L$, $n(y) \cong n(0) \pm (y/L)\Delta n$, $\Phi_0 \Delta n \cong \mu_0 H_p$). For the critical current I_c of a spatially inhomogeneous Josephson contact in high magnetic field the formula

$$I_c = I_{co}/(1 + (qr)^2)^{1/2} \tag{12}$$

is applied [2]. Here r is the correlation radius of spatial fluctuations of the Josephson critical current, $r \ll W$, the contact width, $q = d\varphi/dx$. Hence, using Eq. (4, 12) we get Eq. (5).

There are two main features in hysteretic phenomena, namely, the depression of the critical current at $H = 0$,

$$J_c(0)\downarrow/J_c(0)\uparrow \simeq J_c(\lambda j_{cg})\uparrow/J_c(0)$$

and a shift ΔH of max (J_c) vs H position, where $\uparrow$ and $\downarrow$ indicate the J_c values for the case of increasing and decreasing field at a given value H. According to (5) the maximum of Josephson critical current in decreasing field must be observed in the vicinity of field $H \cong \Delta H$, where

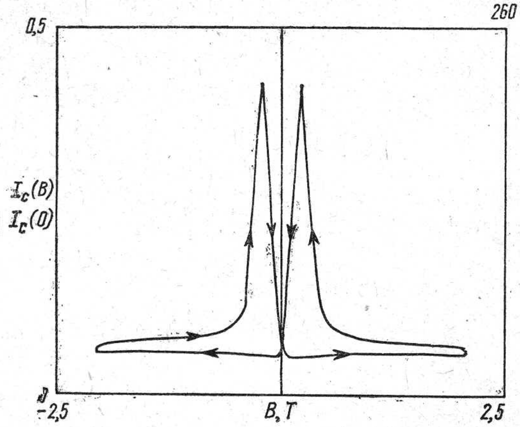
$$q \sim j_s(\Delta H) \cong j_{sm} - j_{cg} \cong 0. \qquad (13)$$

If $H_{c1} > \lambda j_{cg}$ then the field $\Delta H = j_{cg}(\Delta H) \cdot \lambda$. In another limit $H_{c1} < \lambda j_{cg}$ and for the Kim — Anderson model [14]

$$j_{cg}(B) = j_{ka}/(1 + B/B_{ka}), \ \mu_0 \Delta H \cong B_{ka}[(j_{ka}\lambda)/H_{c1} - 1], \qquad (14)$$

here B_{ka} and j_{ka} are the Kim — Anderson model parameters, and for the maximum of external field H_m the condition $H_m \gg H_p + H_{c1}$ is assumed $H_p \cong L \cdot j_{ka}$. For the fields $H_{c1} < H < H_p + H_{c1}$ the ΔH value depends on the maximum field H_m.

Fig. 1 shows the full hysteresis loop $I_c\{j_s(H)\}$ vs H calculated for the situation where the external magnetic field H is varied between $-H_m$ and H_m (see Appendix).



The theoretical hysteresis loop $I_c(B)$ calculated from eq. (A.3—A.15) for the rarameters $I_{f0}/I_0 = 0.5$, $w/r = 100$, $t = 0.001\ \mu m$, $B_{AK} = 0\ 5T$, $J_{KA} = 10^{11}$, $B_{c1} = 0.016T$, $B_{c2} = 34T$, $\lambda = 0.2\mu m$, $H_m = 2T$, $w = L = 2\mu m$.

The expressions (5, 12), (A3—A15) allow to explain the well-known [15, 16] double-step behavior of ceramic critical current J_c vs magnetic field. The first drop in J_c occurs for $\mu_0 H \ll B_0 \cong \Phi_0/S_0$ and can be interpreted as evidence for a weak-link limitation on the transport critical current. Here $S_0 \cong D^2 (\lambda_j \gg D)$ or $S_0 \cong 2\lambda W$ $(W < \lambda_j)$. This is followed by a plateau regime at magnetic fields

$$\mu_0 H_p \ll \mu_0 H \ll B_{j2}$$

where $H_p = j_{cg} L$. The second drop in J_c occurs at the high enough fields $\mu_0 H \gg B_{j2}$ where the field part of $q = d\varphi/dx$ (5) is predominated and the critical current of the Josephson contacts (12) must reduce as $1/H$. At this point the value $S_0 \cong 2\pi t \cdot r \ll 4\pi\lambda W$ and the corresponding characteristic magnetic field

$$B_{j2} = \Phi_0/(2\pi t r) \gg B_0 \cong \Phi_0/(4\pi\lambda W).$$

5. Conclusions

In fields $H > H_{c1}$ the Abrikosov vortices enter the granules of ceramics As a result the critical current of intergranular Josephson contacts depends on the magnetic history of the sample [4—9, 17—21]. But a gradient of the vortex density creates an additional surface current in the granules j_{cg} [20] which depresses the critical currents of the Josephson contacts. Therefore the ceramics with smaller j_{cg} value can have better J_c vs H dependence. The similar improvement of the J_c vs H dependence could be achieved by reduction of the granule thickness $D < \lambda$, when the granular surface current decreases [21].

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Appendix

In this Appendix, we calculate the full hysteresis loop $I_c(H)$ for the situation where the magnetic field H is varied between the extremes — H_m and H_m. To avoid the complication of demagnetizing factors, the grains are approximated by superconducting slabs of the thickness $2L$ (in the Y — direction), the height h (in the Z — direction) and the length W (in the X — direction) with $W \gg L$ and $h \gg L$. The analysis is based on eq. (11) and on the simple Bean approximation for the concentration n (y) of the Abrikosov vortices

$$n(y) \cong n(0) \pm (y/L)\Delta n; \quad \Phi_0 \Delta n = \mu_0 H_p, \qquad (A.1)$$

$H_p = j_{cg} L$. The exact solution (11) of the generalized London equation

$$B - \lambda^2 \cdot d^2B/dy^2 = \Phi_0 \cdot n(y)$$

is fixed by the boundary condition that, at the granule surface ($y = \pm L$) the value $B(\pm L)$ and the external field H, can be in equilibrium, and B takes the value given by the Abrikosov's relation between B and H. The diamagnetic Abrikosov magnetization can be approximated by [12, 13]

$$M_{eq} \cong \begin{cases} -\mu_0 H & -H_{c1} \leqslant H \leqslant H_{c1}, \\ \pm\varepsilon\mu_0 H_{c1}(1 - |H|/H_{c2}) & |H| > H_{c1} \end{cases} \qquad (A.2)$$

$\varepsilon \sim 1$. For the first field interval there is only the Meissner current and the parameter $\beta = (\Phi_0/4\pi\lambda)q$, $q = d\varphi/dx$ is given by:

$$\beta = (\mu_0 H)\tanh(L/\lambda), \ 0 \leqslant \mu_0 H \leqslant B_{c1}. \qquad (A.3)$$

For the second interval

$$\beta = B_{c1}\tanh(L/\lambda) + \alpha(B)\lambda\{1 - \cosh(l/\lambda)/\cosh(L/\lambda)\},$$
$$B_{c1} \leqslant \mu_0 H \leqslant B_{p1}, \qquad (A.4)$$

where

$$B = \mu_0 H, \ \alpha = \mu_0 j_{cg}(B, T), \ l = L - (B - B_{c1})/\alpha(B), \ B_p = \alpha(B_p)L,$$
$$B_{p1} = B_p + B_{c1}$$

For the third interval

$$\beta = B_{c1}\tanh(L/\lambda)(1 - B/B_{c2}) + \alpha(B)\lambda\{1 - 1/\cosh(L/\lambda)\},$$
$$B_{p1} \leqslant \mu_0 H \leqslant B_m. \qquad (A.5)$$

For $B_m - 2B_h \leqslant \mu_0 H \leqslant B_m$ and decreasing field H

$$\beta = B_{c1}\tanh(L/\lambda)(1 - B/B_{c2}) - \alpha(B)\lambda\{1 - 2\cosh(m/\lambda)/\cosh(L/\lambda) +$$
$$+ 1/\cosh(L/\lambda)\} - [\sinh(m/\lambda)/\cosh(L/\lambda)]\{B_m - B - B_h +$$
$$+ \alpha(B)\lambda(2m/\lambda - L/\lambda)\}, \qquad (A.6)$$

where

$$m = L - (1/2)(B_m - B)/\alpha(B), \ B_h = \mu_0 H_h = \alpha(B_m)L.$$

For the fifth interval

$$\beta = B_{c1}\tanh(L/\lambda)(1 - B/B_{c2}) - \alpha(B)\lambda\{1 - 1/\cosh(L/\lambda)\},$$
$$B_{c1} \leqslant \mu_0 H \leqslant B_m - 2B_h. \qquad (A.7)$$

For $-B_{c1} < \mu_0 H \leqslant B_{c1}$

$$\beta = B \cdot \tanh(L/\lambda)\{1 - |B|/B_{c2}\} - \alpha(B)\lambda\{1 - 1/\cosh(L/\lambda)\}. \qquad (A.8)$$

For $-B_m < \mu_0 H < -B_{c1}$ and increasing $|H|$

$$\beta = -B_{c1}\tanh(L/\lambda)(1 - |B|/B_{c2}) - \alpha(B)\lambda\{1 - 1/\cosh(K/\lambda)\}. \qquad (A.9)$$

When $-B_m \leqslant \mu_0 H \leqslant 0$ and $|H|$ decrease

$$\beta = -\beta_{4-6}(|H|), \qquad (A.10)$$

where β_{4-6} is the β value for the 4 — th $\div$ 6 — th intervals ($H > 0$), see eq. (A.6 — A.8). The full β value is

$$\beta = \beta_1 + t/(2\lambda)B, \qquad (A.11)$$

here the second term $(t/2\lambda)B$ takes into account the magnetic flux in the intergranular space, t is the distance between the superconducting granules, the value β_1 is given by eq. (A.3—A.10).

The critical current I_c of a spatially inhomogeneous Josephson contact (2, 12) can be written in the following form:

$$I_c^2(H) = I_{co}^2 + I_{cf}^2 \qquad (A.12)$$

where I_{c0} is the main part,

$$I_{c0}(H) \cong I_0/(1 + |\beta|/B_0), \qquad (A.13)$$

and for the spatially inhomogeneous term of the Josephson critical current in high magnetic field the formula

$$I_{cf} = I_f/\{1 + (\beta/B_{c2}^{cer})^2\}^{1/2} \qquad (A.14)$$

is applied (see eq. (12)). Here $I_f \approx I_{f0}(2r/W)^{1/2}$, r is the correlation radius of the spatial fluctuations of the Josephson critical current, I_f is the amplitude of these fluctuations [2], $r \ll W$, W is the contact width, $B_0 \cong \Phi_0/S_0$, S_0 is the «quantization cell» $S_0 = 2\lambda W$; the second ceramic «critical field»

$$B_{c2}^{cer} = \Phi_0/(4\pi\lambda r). \qquad (A.15)$$

The full hysteresis loop for $I_c(H)$ (fig. 1) was calculated from eq. (A.3—A.15).

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