Mechanisms of heat transport across a nano-scale gap in heat assisted magnetic recording

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Abstract

It is expected that further increases in the data density of hard disk drive magnetic recording systems will require that the read-write head be placed as close to the magnetic media as about 3 or 4 nm, and that it will get some assistance to lower the media's required high coercivity to permit writing. Such assistance could be provided by local heating of the media to about 400°C, and presently much industrial effort is focused on the realization of the heating by a laser. The use of laser optics is well developed for optical recording, but its adaptation to magnetic recording is not straightforward because the light from currently available lasers cannot be efficiently focused down to the required spot of less than 30 nm, and because of the design, integration and reliability issues.

In this paper we compare different mechanisms of heat transport across nano-scale gaps and suggests that local heating for HAMR with sub-5nm spacing can be more efficiently achieved by a Joule heater that is simpler to fabricate than laser-based optical systems and is less destructive for the nano-scale transducers than laser radiation which may lead to their structural damage and short duration life of nanoscale transducers. This paper also outlines a rigorous approach to the analysis of heat transport in nano-scale layered structures like those arising in the HAMR systems and elsewhere.

1 Introduction

Heat Assisted Magnetic Recording (HAMR) requires heating of a small, about 25×25nm, spot on a disk surface located within a few nanometers from a flying head slider. Since the disk should not be scratched, any HAMR system must include a transducer providing contactless delivery of energy to the disk. In most existing prototypes of HAMR systems such transducers include plasmonic devices that convert the electromagnetic energy generated by a laser to collective oscillations of electrons that are coupled with the electromagnetic field on the disk surface. So far, considerable progress has been achieved in understanding the mechanisms of the conversion of the laser energy to plasmons. However, the mechanism of the energy passage across a nano-scale gap between the transducer and the disk is still not adequately studied.

It is certain that the energy flow between the transducer and the disk is due to electromagnetism. However, this flow cannot be computed by the conventional theory of radiative heat transfer because several of the key assumptions of this theory are not valid in the nanoscale, and also because the radiation is not the only mechanism of heat transfer provided by electromagnetic phenomena.

It is easy to see that the macroscopic Maxwell equations and Ohm's law, formulated in terms of the permittivity and permeability of the media, are not always valid for nanoscale metallic structures. Indeed, as pointed out in [24, §45,§56,§67], these equations are obtained by the averaging of the exact microscopic Maxwell equations, which is an operation that can only be justified when the fields remain essentially constant within distances comparable to the mean free paths traveled by electrons between collisions and in one cycle of oscillations. However, this condition *"is, in fact the first to be violated in metals as the frequency increases"* [24, §45]. Thus, infrared electromagnetic radiation penetrates good conductors like gold within the depth of the skin layer which is of the order $\sim 30\,\mathrm{nm}$, comparable with the mean free path traveled by conduction electrons in gold between collisions at room temperature. This phenomenon, known as the anomalous skin effect, implies that inside the skin layer the interaction of infrared radiation with gold at room temperature does not follow the macroscopic Maxwell equations and Ohm's law. When the frequency increases to the visible band, the field gets appreciably changed in the surface layer of thickness comparable with the mean free path traveled by conduction electrons in one cycle of oscillations [27]. In the middle of the visible band this mean free path is of the order $f_\circ \sim 3\,\mathrm{nm}$, which implies that the macroscopic Maxwell equations and Ohm's law are not valid within a few nanometers from the surface of the metal, and thus they cannon be applied to analyze the electromagnetic processes inside a 20 nm thick gold transducer integrated into a HAMR head.

The failure of the macroscopic Maxwell equations is not the only nanoscale-related inconvenience which complicates the understanding of heat delivery in a HAMR system.

Another difficulty arises from the impossibility of computing the net heat flux between two bodies at different temperatures by a formula based on the difference of two Planck's expressions representing the radiations from each of the bodies. As discussed in [5], such an approach is generally incorrect because Planck's law is valid only in equilibrium, i.e., when the net heat flux vanishes *a priori* [16, 17, 23, 30]. It is well known that the error of this approach is negligible if the width of the gap considerably exceeds the characteristic wavelength of thermal radiations [18], but this is not the case in HAMR systems.

Finally, it is important to emphasize that although all of the heat transport between narrowly separated bodies is provided by electromagnetism, it is not accurate to say that all heat is carried by the electromagnetic radiation. Indeed, as explained in [17, Lecture 31]] the electromagnetic field generated by a moving charge consists of both the radiative component that dominates far away from the source and a quasi-static field that dominates near the source. The latter field gives

rise to intermolecular forces [20] that keep a solid together, prevents molecules from direct contact during collisions, provides interaction between slightly separated bodies, and is responsible for the elastic properties of materials, including their ability to support lattice vibrations. Due to these forces the lattice ions and electrons from different sides of a narrow gap exchange momenta, and thus provide additional channels of heat transport between bodies [8], which are negligible if the separation exceeds 20 nm, but which become extremely powerful for gaps narrower than 10 nm.

The above suggests that heat transfer in nanoscale structures relevant to HAMR cannot be explained by conventional approaches to thermal radiation based on the macroscopic Maxwell equations and Ohm's law, as well as by Planck's law of equilibrium thermal radiation. On the other hand, to design a reliable HAMR device it is necessary to understand the mechanisms of heat transfer across the head-disk interface. Therefore, the development of new methods for the analysis of nanoscale heat transfer appears as an important scientific problem required to determine the success of the HAMR project. Since the development of a complex set of new methods may not happen within a few months and requires substantial research in a new area it seems practical to start with an asymptotic analysis that captures the main features of the involved processes and produces insightful quantitative order-of-magnitude estimates that may later evolve into accurate computational procedures. An overview of such asymptotes and of their underlying ideas are presented below.

2 Near-field of a moving charge and its role in heat transfer across a gap

It is well known that the propagation of an electromagnetic field through a material can be viewed as a multi-step process [17], where the incident field excites the motion of charged particles in the material, and then the moving charges generate a secondary field which interferes with the original field thereby creating a total field whose averaged characteristics are described by the Maxwell equations for continuous media. In order to understand the structure of the electromagnetic field near the transducer it suffices to consider the near field of a single charge and then analyze the superposition of the fields from many charges.

Let a charge q vibrate near an equilibrium position $X_0 = (x_0, y_0, z_0)$. For transparency we assume that the charge moves only along the x-axis, so that its position at time t is described by the one dimensional harmonic vibration formulas

$$x = x_0 + d\sin(\omega t - \alpha), \qquad y = y_0, \qquad z = z_0, \tag{2.1}$$

where

$$0 \le d < 1\,\text{nm}, \tag{2.2}$$

which means that the amplitude of the vibration is comparable to the interatomic distance. Then,

the electric field at O has the value [17]

$$\boldsymbol{E} = \frac{q}{4\pi\epsilon_0}\left[\frac{\boldsymbol{e}_r}{r^2} + \frac{r}{c}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\boldsymbol{e}_r}{r^2}\right) + \frac{1}{c^2}\frac{\mathrm{d}^2\boldsymbol{e}_r}{\mathrm{d}t^2}\right], \tag{2.3}$$

where c is the speed of light and $r = r(t')$ is the distance from O to the position of the charge $X(t')$ at the retarded time t', i.e. when the signal reaching the observer O at the moment t was emitted. Since the charge moves considerably slower than light, the retarded time can be approximated as $t' \approx t - r(t)/c$, and if we additionally assume that the observer is located close to the charge, then the delay $\Delta t = r(t)/c$ can be neglected, resulting in the approximations $t' \approx t$ and $r = r(t') \approx r(t)$. Similarly, although $\boldsymbol{e}_r$ is defined as the unit vector in the direction from the center O to the point $X(t')$, in the considered case $\boldsymbol{e}_r$ can be viewed as a unit vector in the direction from O to $X(t)$.

Observing that $\boldsymbol{e}_r = (e_x, e_y, e_z)$, where

$$e_x = \frac{x_0}{r} + \frac{d\sin(\omega t - \alpha)}{r}, \quad e_y = \frac{y_0}{r}, \quad e_z = \frac{z_0}{r}, \tag{2.4}$$

and taking into account (2.2), we find that the excited electric field can be represented as

$$\boldsymbol{E} = \boldsymbol{E}_0 + \boldsymbol{E}_1 + \boldsymbol{E}_\infty, \tag{2.5}$$

where the first term

$$\boldsymbol{E}_0 = \frac{q(x_0\boldsymbol{i} + y_0\boldsymbol{j} + z_0\boldsymbol{k})}{4\pi\epsilon_0 r^3} = \frac{q}{4\pi\epsilon_0}\frac{\boldsymbol{e}_r}{r^2} \tag{2.6}$$

represents the static Coulomb field, the second term

$$\boldsymbol{E}_1 = \frac{qd\omega\cos(\omega t - \alpha)\boldsymbol{i}}{4\pi\epsilon_0 c r^2}, \tag{2.7}$$

corrects the Coulomb field by including into consideration the retardation caused by the finiteness of the speed of light, and the third term

$$\boldsymbol{E}_\infty = \frac{qd\omega^2\cos(\omega t - \alpha)\boldsymbol{i}}{4\pi\epsilon_0 c^2 r} \tag{2.8}$$

describes the radiation.

To understand the relative importance of the components of (2.5) we introduce the wavelength $\lambda = 2\pi c/\omega$, and observe that (2.6)–(2.8) together with (2.2) imply the estimates

$$|\boldsymbol{E}_1| < \frac{2\pi d}{\lambda}|\boldsymbol{E}_0|, \qquad |\boldsymbol{E}_\infty| < \frac{4\pi^2 r d}{\lambda^2}|\boldsymbol{E}_0|, \tag{2.9}$$

where d is the amplitude of oscillations defined by (2.2).

Let the wavelength be in the range of 500–900 nm, and let the distance between the charge and the observer be about $r \approx 25$ nm, corresponding to the longest distance between a point on a

25 nm wide bottom of the transducer and a point on its footprint on the disk separated from the transducer by a 5 nm gap typical for a modern hard drive. Then, (2.2) implies the estimates

$$|\boldsymbol{E}_1| \ll 0.01|\boldsymbol{E}_0|, \qquad |\boldsymbol{E}_\infty| \ll 0.005|\boldsymbol{E}_0|, \tag{2.10}$$

which show that at a short distance $r \leq 5\,\text{nm}$ the electric field generated by a charge vibrating with an optical frequency is essentially reduced to its static Coulomb field.

The above implies that if two material bodies are separated by a narrow gap then, due to non-radiative short range intermolecular forces, the motion of electric charges in one body is transmitted to the motion of electric charges in the other body, and this means that the intermolecular forces cause heat transfer between closely separated bodies. The mechanism of heat transfer provided by short-range intermolecular forces is different from the radiative heat transfer caused by long-range electromagnetic radiation. Moreover, intermolecular forces provide heat transport between metals by two different channels: by excitation of lattice vibrations and by excitation of conducting electrons. Indeed, in metals the negatively charged conduction electrons freely move between positively charged ions, which form a vibrating lattice. External electric fields originating in the neighboring body affect the motion of the ions forcing additional lattice vibrations and also excite lighter electrons, which eventually pass the gained energy to the lattice, thus contributing to heat transfer across the gap. This schematic overview makes it obvious that as the distance between closely separated bodies vanishes, the rate of heat conduction between them rapidly increases, approaching the rate of heat exchange between parts of a continuum metal. Such a smooth transition from a gap to a continuum body is necessary for any model of heat transport across the gap. However, conventional approaches don't meet this requirement, but its natural appearance in our approach provides confidence that it captures most characteristic features of nanonscale heat transfer.

3 Transmission of lattice vibrations across a nano-scale vacuum gap

To understand how intermolecular forces provide heat conduction between separated bodies it suffices to consider a one-dimensional mass spring model of a crystalline solid with a nanoscale gap.

Consider first a uniform chain shown in Fig. 1, where equal masses $m = \rho a$ are connected by springs with elastic modulus γ and equilibrium spacing $a > 0$, so that ρ represents the mass density of the chain. Let $\xi(x_n) \equiv \xi_t(x_n)$ be the displacement at time t of the particle identified by its equilibrium position $x_n = an$. Then the motion of these particles is described by the equation

$$\rho a^2 \ddot{\xi}(x_n) = \gamma \left[\xi(x_{n+1}) + \xi(x_{n-1}) - 2\xi(x_n)\right]. \tag{3.1}$$

When $a \to 0$ while the density ρ remains constant, the nodes x_n become continuously spread over the real line and these equations converge to the wave equation $\ddot{\xi}(x) = v^2 \nabla^2 \xi(x)$, where x is a continuous coordinate and $v = \sqrt{\gamma/\rho}$ is the sound speed determined by the elastic modulus γ and by the mass density $\rho = m/a$ of the continuum.

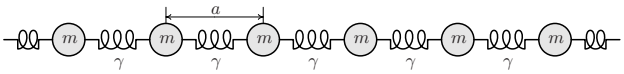


Figure 1: Mass-spring models of a continuum medium

Generalizations of this model can accurately describe any feasible anisotropic elastic medium, but to estimate the heat carrying capability of lattice vibrations it suffices to use Debye's theory [16, 25], which treats any solid as an isotropic continuum supporting propagation of scalar acoustic waves with the wave speed v determined by the material. In this theory the energy flux carried by thermal vibrations at room or higher temperature T can be characterized by the value

$$Q^{ac} \approx 3vN\kappa_B T, \tag{3.2}$$

where $\kappa_B \approx 1.4 \cdot 10^{-23}\mathrm{m}^2\mathrm{kg/s}^2$ is the Botlzmann constant, $N = \rho/A_r u_a$ is the number of atoms per unit volume represented in terms of the mass density ρ, atomic weight A_r and the atomic mass unit $u_a = 1.7 \cdot 10^{-27}\mathrm{kg}$, which is essentially the weight of a single proton. For gold $A_r \approx 200$, $\rho \approx 2 \cdot 10^4\mathrm{kg/m}^3$, $v \approx 2 \cdot 10^3\mathrm{m/s}$, and (3.2) shows that gold's lattice at room temperature may carry flux up to the order of $\sim 1.5 \cdot 10^{12}$ $(\mathrm{W/m}^2)$, which is sufficient for HAMR purposes [10, 12, 34].

The mass-spring model of the continuum can be extended to a more complex case describing two continuous half-spaces separated by a narrow, but non-vanishing gap.

Consider next the chain shown in Fig. 2 where the masses $m_- = \rho_- a$ are located at the nodes $x_n = an < 0$ and the masses $m_+ = \rho_+ a$ are located at $x_n = h + an$, where $n \geq 0$ and $h > 0$. Assume that the springs inside the half-chains $x < 0$ and $x > h$ have the elastic moduli γ_- and γ_+, respectively, and the spring connecting x_{-1} and x_0 has the modulus γ_h.

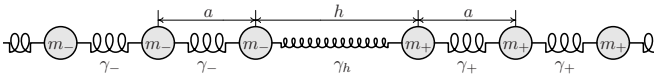


Figure 2: Mass-spring models of two media separated by a narrow gap

The motion of this chain is described by equations similar to (3.1) that control the motion of all particles with $n \neq -1$ and $n \neq 0$, and by two additional equations for the particles at the ends of the uniform half-chains

$$\begin{aligned} \rho_- a\ddot{\xi}(0) &= \frac{\gamma_h}{h}\big[\xi(h) - \xi(0)\big] + \frac{\gamma_-}{a}\big[\xi(-a) - \xi(0)\big], \\ \rho_+ a\ddot{\xi}(h) &= \frac{\gamma_h}{h}\big[\xi(0) - \xi(h)\big] + \frac{\gamma_+}{a}\big[\xi(h+a) - \xi(h)\big]. \end{aligned} \tag{3.3}$$

If $a \to 0$ but h remains finite then (3.3) reduce to the interface conditions

$$\gamma_- \frac{\partial\xi(x)}{\partial x}\bigg|_{x=0} = \gamma_+ \frac{\partial\xi(x)}{\partial x}\bigg|_{x=h} = \gamma_h \frac{\xi(h) - \xi(0)}{h}, \tag{3.4}$$

which compliment the wave equations describing the motions in the homogenous domains.

If the interconnection $0 < x < h$ is very strong in the sense that $\gamma_h/h \to \infty$ then (3.4) reduce to the single condition $\xi(h) = \xi(0)$, which implies that the boundaries $x = 0$ and $x = h$ are firmly connected to each other so that the motion of one of them exactly copies the motion of the other. In the opposite case of a very weak connection when $\gamma_h/h \to 0$, conditions (3.4) reduce to Neumann boundary conditions $\xi'(0) = \xi'(h) = 0$, which imply that the domains $x < 0$ and $x > h$ move independently of each other.

The latter one-dimensional model can be generalized to a three-dimensional model of two half spaces separated by a narrow gap of width h. In this model heat is carried by lattice vibrations described in terms of the pressure $p(\boldsymbol{r})$ related to the displacement vector field $\boldsymbol{\xi}(\boldsymbol{r})$ by $\rho\ddot{\boldsymbol{\xi}} = -\boldsymbol{\nabla} p$. The pressure satisfies the wave equations

$$\frac{\partial^2 p}{\partial t^2} = c_\pm^2 \nabla^2 p, \qquad c_\pm = \begin{cases} \sqrt{\gamma_-/\rho_-}, & x < 0, \\ \sqrt{\gamma_+/\rho_+}, & x > h, \end{cases} \tag{3.5}$$

describing the motions in the homogenous half-spaces and it also obeys the interface conditions

$$\gamma_- \frac{\partial^2 p}{\partial x^2}\bigg|_{x=0} = \gamma_+ \frac{\partial^2 p}{\partial x^2}\bigg|_{x=h} = \frac{\gamma_h}{h}\left(\frac{\partial p}{\partial x}\bigg|_{x=h} - \frac{\partial p}{\partial x}\bigg|_{x=0}\right) \tag{3.6}$$

which generalize (3.4) and describe the interaction between separated half-spaces. Is should be noticed that the pressure field p is defined in the half-spaces $x < 0$ and $x > h$ but is not necessarily defined inside the gap $0 < x < h$.

To estimate the energy flux that can be carried by lattice vibrations between separated half-spaces, we first observe that it has the order of

$$Q_h^{ac} \sim |K_h|^2 \left\langle E_\pm^{ac} v_\pm \right\rangle, \tag{3.7}$$

where $\left\langle E_\pm^{ac} v_\pm \right\rangle$ is the mean value of the products of the energy density and the wave speed in the half-spaces $x < 0$, $x > h$, and K_h is the transmission coefficient of a gap of width h, which can be computed by the methods of the theory of wave propagation in layered media [1, 15]. This theory implies that if the gap is wider than the wavelength Λ of thermally excited lattice vibrations, which is about 1nm at room temperature, then

$$|K| \approx \frac{\gamma_h \Lambda}{\gamma_0 h}, \qquad \big(h \gg \Lambda \approx 1\text{nm}\big), \tag{3.8}$$

where γ_0 is the average elastic moduli of the half-spaces, and γ_h is the elastic modulus of the vacuum gap. Also, if h is large compared to the intermolecular distance then γ_h can be estimated as

$$\gamma_h = h\left|F'(h)\right|, \tag{3.9}$$

where $F(h)$ is the resultant of van der Waals forces acting between molecules belonging to the different half-spaces separated by the distance h. This force, predicted in 1948 [9], has been

intensively studied, and, as shown in [20, 24], for sufficiently small h it has the asymptote

$$F(h) \approx \frac{C}{h^3}, \qquad h \ll \lambda_0 \approx 500\text{nm}, \tag{3.10}$$

where $\lambda_0 \approx 500$nm is the dominant wavelength of the electromagnetic thermal radiation. Correspondingly, the modulus γ_h has the asymptote

$$\gamma_h \approx \gamma_0 \frac{a^3}{h^3}, \tag{3.11}$$

where the factor $\gamma_0 a^3$ is determined by an assumption that as h reduces to the interatomic distance a, then γ_h should approach the average γ_0 of the elastic moduli of the half-spaces.

Finally, combining formulas (3.7)–(3.11) we conclude that the heat flux carried by lattice vibrations across a gap of width h is of order

$$Q_h^{ac} \sim \left(\frac{a}{h}\right)^8 \left(\frac{\Lambda}{a}\right)^2 \left\langle E_\pm^{ac} v_\pm \right\rangle, \tag{3.12}$$

where C is a constant determined by a temperature differential and Λ is the typical wavelength of thermal lattice vibrations.

As mentioned in Section 2, intermolecular forces provide heat transport between slightly separated metallic bodies not only by pushing and attracting lattice ions, but also by pushing and attracting conduction electrons. Since conduction electrons are mobil and almost 1800 times lighter than ions, their reaction on electric fields is much stronger than that of ions, and this explains why thermal conductivity of metals is almost three orders of magnitude higher than of dielectrics ($\sim$ 400W/mK for Cu or Ag, and $\sim$ 1W/mK for glass or porcelain). Indeed, while metals and dielectrics have comparable lattice conduction, in metals, mobil and light electrons carry about two orders of magnitude more heat that lattice vibrations. If the metals are separated by a gap, then, since electrons cannot cross it, there is no direct electrical current between metals. However, if the gap is sufficiently narrow, then the electrons react to the intermolecular forces exerted from the opposite side and, without a chance to flow, move chaotically producing heat and passing it to the lattice. Since the motion of electrons between lattice ions is described by the Schrödinger equation with a periodic potential, which has similar properties to those described by the wave equation controlling lattice vibrations, their contribution of electrons to heat transfer across the gap can be estimated by methods similar to that developed for the analysis of lattice vibrations. As a result the heat flux across the gap between metals provided by electrons appears to be about two orders of magnitude higher than that described the formula (3.12). It is worth mentioning that the outlined model of heat transfer between slightly separated metals implies that as the width of the gap approaches the interatomic distance, the total heat transfer across the gap approaches the heat transfer in a continuous medium. Although such merge appears to be natural and mandatory for any model of heat transport across the gap, it, nevertheless, is not met by conventional approaches.

4 Estimates of the thermal conductance between a HAMR disk and slider

The lattice vibrations discussed in the previous section have sharply different properties from those of the thermal electromagnetic radiation: lattice waves have wavelengths of a few nanometers and cannot cross gaps wider than a few nanometers, electromagnetic radiation has wavelengths of several hundreds of nanometers and can propagate millions of kilometers in vacuum. Despite such contrast, the contributions of lattice vibrations and electromagnetic waves to the thermal conductivity of a nanoscale gap can be described by a unified method, which, however, is not a method customarily used in the theory of radiative heat transport.

To see why conventional methods of radiative heat transport can not be applied to the analysis of heat transfer across a narrow gap it suffices to observe that such methods predict that an imaginary, vanishing, gap between identical materials of a continuous body has a finite thermal resistance, which obviously contradicts the laws of thermodynamics and common sense. Indeed, the conventional approach to radiative heat transfer between bodies A and B maintained at the temperatures T_A and T_B is based on the assumption that the net heat flux can be represented as

$$Q = Q_A(T_A) - Q_B(T_B), \tag{4.1}$$

where the outflux $Q_A(T_A)$ radiated from A to B depends only on temperature T_A and other properties of the body A, but is not affected by any properties of the body B, including its temperature T_B. Similarly, the outflux $Q_B(T_B)$ from B to A does not depend on any properties of A. When this assumption is applied to the case of two bodies A and B of the same material separated by an imaginary vanishingly narrow gap, it shows that the net flux Q between A and B is determined only by the temperatures T_A, T_B and is independent on the properties of A and B. Therefore, there are only two options: either $Q = 0$ always, even when $T_A \neq T_B$, or $Q \neq 0$ even when $T_A = T_B$ and A and B are made from the same material. Since neither of these options can be valid, we see that conventional theory of radiative heat transfer has a systematic flaw that cannot be ignored in the nanoscale.

It should be mentioned that the assumption (4.1) gives reasonable approximations if the heat carrying waves are much shorter than the width of the gap, so that these waves may be decomposed into wave packets that have dimensions much smaller than the width of the gap [17, 18]. However, if the bodies are separated by a 5 nm or smaller gap then neither the lattice vibrations nor the electromagnetic waves discussed above are short enough to form wave packets that have the above mentioned properties required to justify the conventional approach based on (4.1).

The above implies that although thermally excited lattice vibrations and electromagnetic waves have drastically different length scales, from the point of view of propagation across a 5 nm gap these waves belong to the same category, and their contributions should be described by a unified method, which, unlike conventional methods of radiative heat transport, takes into account the wave

properties of these waves. The development of this method was started in papers [2, 4] devoted to the analysis of the interface thermal resistance caused by a mismatch of the material properties of the contacting media. Then, in [6] this method was used to explain the divergence of the radiative heat transport across a vanishingly narrow gap between half-spaces of identical materials. Analysis of the obtained results made it clear that the suggested method admits a far reaching generalization that can be uniformly applied to virtually arbitrary nanoscale layered structures without explicitly accounting for intermolecular interactions, which certainly play an important role at the nanoscale.

The first two steps of the rigorous approach to the nanoscale heat transport carried by waves include the generalization of Plank's law of thermal radiation from strictly equilibrium systems to systems with a steady heat flux [5] and the description of the equilibrium ensembles of waves in layered structures [3]. Then the non-equilibrium ensembles can be described by the method outlined in [4]. This approach can be used to compute the contributions to heat transport between separated half-spaces by any type of waves, including the electromagnetic radiation and lattice vibrations discussed in Section 3. However, the complete theory is not needed for the purpose of getting order-of-magnitude estimates, which may be obtained by a simple qualitative analysis discussed below.

First we estimate the heat transport coefficient carried by electromagnetic radiations. Recent papers [31, 33] report measurements of this coefficient between SiO_2 surfaces at room temperature separated by a gap wider than 30nm. It is also known that when the gap's width h reduces below the wavelength then as $h \to 0$ the heat transport coefficient diverges as $1/h^2$ [6, 31, 33]. Therefore, the experimental data from [31, 33] can be extrapolated to the domain $h < 30$nm resulting in the solid line in Fig. 3. Next we recall from the previous section (see also [8]), the contributions to the heat transfer coefficient of the electromagnetic and lattice vibration waves become equal when the width of the gap drops to approximately $h \approx 5$nm. This information determines the point of intersection of the graphs of these coefficients and makes it possible to extrapolate the heat transfer coefficient of the lattice vibration wave using its expected $1/h^8$ dependence on the width d. Finally, the contribution of electrons whose thermal motion is driven by the same intermolecular forces that drive lattice vibrations is expected to follow the same trend but be as much as two orders of magnitude higher because of electron's higher mobility and suspensibility to the applied force. The resulting curves are shown in Fig. 3 by a dashed line and a dotted lines.

The graphs in Fig. 3 illustrate the observations of the late 1960s that heat transport between bodies separated by sub-micron gaps considerably exceeded the limit predicted by the conventional theory of radiative heat transfer [13, 14, 19] corresponding to the horizontal asymptote for large gaps of the dotted line in Fig. 3. More recent experiments demonstrated that heat transport across 30nm gaps may exceed conventional predictions by three orders of magnitude [31, 33]. The first theoretical explanation of this phenomenon [29] was based on fluctuational electrodynamics

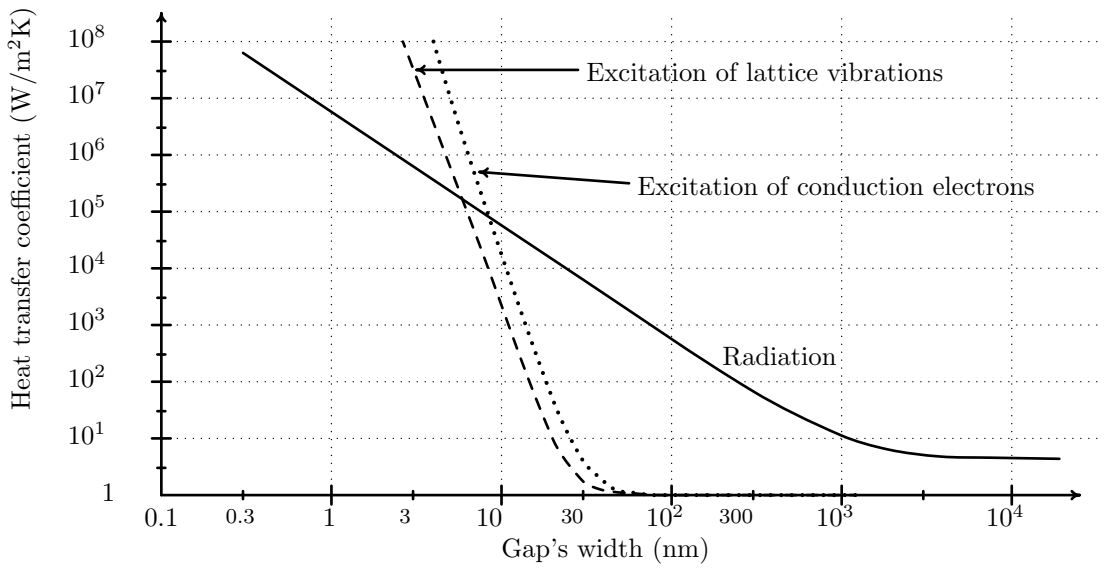
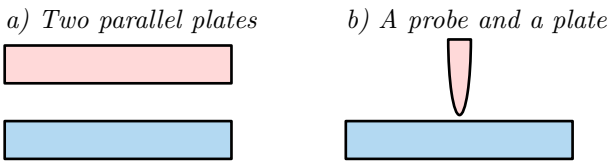


Figure 3: Components of the heat transfer coefficient of a narrow gap

[32], which had also been employed for the analysis of van der Waals intermolecular forces [24]. Later, this theory was enhanced by inclusion into consideration of specific surface waves which may propagate along interfaces between certain materials. Thus, since an interface between polar dielectrics (e.g. SiO_2 and SiC) supports propagation of surface phonon-polaritons (formed due to the coupling of electromagnetic and electron waves), it was proposed that the larger amount of heat transfer across a narrow gap (see Fig. 4a) between such materials is caused by tunneling of phonon-polaritons propagating along different sides of the gap [31, 33]. This explanation, however, is not convincing because it is limited to special materials while heat transfer across a vanishing gap between any materials must approach the rate of heat transfer through direct contact as the gap vanishes, which is many orders of magnitude higher than can be provided by radiation. Also, tunneling of surface waves does not explain the observed enhancement of heat transfer between a structure with non-parallel surfaces, such as shown Fig. 4b, where a plate is approached by a perpendicularly oriented very small radius probe [22, 26, 28].



Enhanced thermal conductance in these structures is caused by direct intermolecular interaction.

Figure 4: Common nano-structures with enhanced thermal conductance

Higher than expected (from the conventional theory) thermal conductance in nanoscale structures like those shown in Fig. 4 is often attributed to different causes, including but not limited to surface roughness, conduction through air and moisture, tunneling of surface and evanescent waves, as well as by electromagnetic fluctuations studied by fluctuational electrodynamics [32]. These factors certainly affect the process of heat transport, but our analysis suggests that the principal part of the increased thermal conductance of gaps smaller than a few microns can be explained by two primary mechanisms. If the gap's width is smaller than a few microns but larger than about ten nanometers, then the analysis of thermal transport must be based on Planck's formula modified to systems with a heat flux [5]. Then, for even narrower gaps, it is necessary to take into account intermolecular interactions between separated bodies [7, 8]. Curiously, this statement agrees with the expectations that experiments with heat transport across nanoscale gaps "can also shed light on the thermal contribution to the Casimir force" [33]. Indeed, our analysis suggests that the enhancement of heat conductance across extremely narrow gaps is caused by Casimir and closely related van der Waals forces, which, therefore, directly contributes to thermal transport.

5 Conclusion: implications for HAMR

The above suggests that the heating of the hard drive magnetic media in HAMR systems can be achieved by use of a Joule heater placed within in a few nanometers from the magnetic layer. To get an idea about the feasibility of such an approach to HAMR we estimate the heat transfer coefficient (heat flux per unit area per unit temperature differential) between the slider and the magnetic layer required to raise the temperature of the recorded spot by 400°C and then compare it with the heat transfer coefficients that can be achieved in practice.

It is generally accepted that the heat transfer coefficient of the gap between the slider and the disk should be as much as $10^8 \mathrm{W/m^2K}$. Therefore, we next check the feasibility of such heat conductance.

In the experiments reported in [33] the heat transfer coefficient between two surfaces separated by a 30nm gap reaches $2.5 \cdot 10^3 \mathrm{W/m^2K}$, which is four orders of magnitude less than required for HAMR purpose. However, the $h = 30$nm separation between surfaces reported in [33] is considerably larger than the physical spacing between the bottom layer of the head slider and the top layer of the disk, which in modern disk drives may be as small as 2nm [11]. To extrapolate the measured results from [33] to smaller separations we first recall that if $h = 30$nm then almost all heat is carried by electromagnetic radiation, and as h decreases this kind of heat transport increases at the rate $1/h^2$. Therefore, when the gap between the heater and the disk overcoat reduces from 30 nm to 2 nm then the radiative heat flux is expected to increase by a factor of 225, thereby boosting the EM heat transfer coefficient to about $6 \cdot 10^5 \mathrm{W/m^2K}$. Moreover, as shown above, when the gap narrows below 10 nm then, in addition to electromagnetic radiation, much

more heat is also carried across a gap due to short range quasi-static intermolecular forces which couple lattice vibrations and electron's motion on both sides of the gap providing contribution to heat conductance that scales as $1/h^8$. In this case the required level of total heat transport across the gap from a Joule heater is certainly realistic. In fact, the required level of heat transfer coefficient in a similar structure consisting of the tip of an AFM and a substrate has been reported in [26], where, however, it was attributed to conduction through the air.

The addition of a Joule heater near the inductive write pole should be relatively straight forward. Indeed, one heater is already supplied in existing heads in the vicinity of the read/write transducer in order to control the 2 nm spacing through thermal flying-height control. The Joule heater for HAMR can be placed at the location proposed for laser heating in current HAMR concepts. It could be a straight heater core heated by a resistive coil placed on a larger element that tapers to the size of the data bit at the interface, similar in dimension as the write pole tip. Alternatively, it could be a core element that is heated without a coil by attaching heater wires at the top and close to the bottom of the element. It may even be possible to use the same pole for the inductive write element and the heater element thereby having the magnetic write flux and the heat flux emanate from the same pole tip. While there may need to be some insulating material around the heater to keep the heat from escaping along its sides, all of the required modifications from present perpendicular write heads should be manageable using existing head fabrication methods, thereby providing a great advantage over what is required to integrate a laser and a near-field optical transducer in the head.

Finally, we note that Joule heating for HAMR has been proposed previously in [21, 35]. These patents focused on the structural fabrication of the system, but they gave no analysis of the heat transport in layered nano-scale structures and the gap spacing limitations. At the time of this patent the spacing between the slider and disk was more than 10 nm, which is beyond the range where our analysis shows Joule heating can be effective. If this assertion is correct then it implies that the HAMR systems can be made significantly simpler and cheaper by resistive heating than by laser heating.

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