Intergranular exchange coupling

M. W. Muller and R. S. Indeck

Department of Electrical Engineering, Washington University, St. Louis, Missouri 63130

(Received 10 June 1993; accepted for publication 29 October 1993)

We evaluate the exchange interaction between neighboring grains of a polycrystalline magnetic material with uniaxial magnetocrystalline anisotropy, based on the energy of the domain wall formed at the portion of the interface in atomic contact. The analysis suggests that previous work [J.-G. Zhu and H. N. Bertram, in Solid State Physics Vol. 46, edited by H. Ehrenreich and T. Turnbull (Academic, San Diego, 1992)] may underestimate the interaction, and it predicts a different dependence on grain size.

If the grains of a polycrystalline magnetic material are too small to sustain a domain wall, then each grain will be, effectively, a single domain particle. Moreover, if adjacent grains are in sufficiently close contact, they can be coupled by an exchange interaction that may favor a subset of their possible magnetization orientations. For example, if the magnetocrystalline anisotropy of the grains is uniaxial, ferromagnetic exchange will favor states in which the magnetizations of adjacent grains are more nearly parallel than antiparallel. In this communication we develop a new estimate of the magnitude of the intergranular exchange interaction. Such an estimate should be useful in modeling magnetization processes in magnetic recording media, a topic that has attracted a good deal of attention recently.1

The exchange interaction in a ferromagnet is commonly represented as an effective “exchange field” acting on the atomic dipole moments. In this representation the exchange energy density \( \omega_e \) has the form

\[
\omega_e = 2M \cdot H_e,
\]

where \( M \) is the magnetization of the magnetic medium and \( H_e \) the effective exchange field. In a continuous medium \( H_e \) is proportional to the Laplacian of \( M \), the proportionality constant including the exchange constant \( C \) (or \( A \)). In order to extend this formalism to the exchange interaction between a pair of grains, the effective field at each grain and the magnetization of each grain are approximated as being uniform. Then the exchange field \( H_{ij} \) contributed at grain \( i \) by nearest neighbor \( j \) is defined by that neighbor’s contribution \( W_{ij} \) to the exchange energy:

\[
W_{ij} = 2m_i \cdot m_j \cdot H_{ij} V_i,
\]

where \( V_i \) is the volume of grain \( i \) and where \( m_i \) and \( m_j \) are unit vectors. To evaluate this interaction it has been assumed1 that the magnetization direction rotates linearly between the centers of grains \( i \) and \( j \). A more realistic estimate should recognize that adjacent grains may be in contact over only part of the facing areas. The grain boundaries usually consist, at least in part, of nonmagnetic, weakly magnetic, or even paramagnetic materials, and the intergranular exchange coupling usually is considered to be weakened by the grain boundaries. In these portions of the boundaries the magnetization orientation can change abruptly with little or no energetic penalty. In the interfacial regions where the grains are in direct atomic contact, the magnetic structure of the contact region is a domain wall whose energy per unit area will be given to a good approximation by the bulk value. Accordingly, taking the zero of energy to be given by the grains’ magnetizations being parallel \( m_i = m_j \), the energy (positive) of a pair of grains with atomic contact area \( a_{ij} \) is simply \( \gamma_a a_{ij} \), where \( \gamma_a \) is the wall energy per unit area, so

\[
\frac{1}{2} (1 - m_i \cdot m_j) M_i H_{ij} V_i = \gamma_a a_{ij}
\]

and

\[
H_{ij} = M_i H_{ij} m_j = \frac{2 \gamma_a a_{ij}}{(1 - m_i \cdot m_j) M_i V_i m_j}.
\]

The wall energy density \( \gamma_a \) depends on the orientations of the grains’ easy axes relative to the interface. The grains of most storage media are uniaxial, and we confine our discussion to such media, whose magnetocrystalline anisotropy energy is given by \( W_k = K \sin^2 \phi \) with \( K > 0 \) and \( \phi \) the angle between \( M \) and the easy axis. Results analogous to those we will report can readily be derived for other forms of the magnetocrystalline anisotropy.

If the angles formed by the easy axes of two adjacent grains with the normal to the interface are different, the domain wall at the interface must carry magnetic charge and therefore dipolar energy. Unlike the anisotropy energy of the wall, this part of the wall energy must not be ascribed to the exchange coupling, since the magnetic charge also present at the interface in the absence of the wall.

We assume that the grains are in atomic contact, so that \( M \) changes continuously across the interface. The magnetization in the (approximately) uniformly magnetized region of each grain does not necessarily line up in the direction of a magnetocrystalline easy axis since it must lie along the sum of all the applied and effective fields. However, the energy associated with a deviation of \( M \) from this direction must still be quadratic for small deviations, and we approximate it as a uniaxial anisotropy of the form \( K \sin^2 \phi \). With this approximation we can use standard methods3 to calculate the energy per unit area of the wall as

\[
\gamma_a = 2 \sqrt{KA} (1 - m_i \cdot m_j).
\]

Thus we have the (at first glance, surprising) result that \( H_{ij} \) is independent of the domain wall angle.
\[ H_{ij} = \frac{4\sqrt{KA_{ij}}}{M_iV_i} m_j. \]

It is common practice\(^1\) in magnetic recording applications to normalize all magnetic fields to the effective anisotropy field \( H_K = 2K/M \). With this normalization \( h_i = MH_i/2K \) is then given by

\[ h_{ij} = 2 \sqrt{\frac{A}{K}} \frac{a_{ij}}{V_i} m_j = \frac{2}{\pi} \frac{\delta_0 a_{ij}}{V_i} m_j, \]

where \( \delta_0 \) is the normal thickness of a 180° wall.

To compare our result with the treatment given in Ref. 1, we assume a thin film geometry such that \( a_{ij}/V_i = f/D \), where \( D \) is the linear dimension of the grain and \( f \) the fraction of the facing surfaces in contact. The exchange density due to all nearest neighbors becomes

\[ w_e = \frac{2f}{D} \frac{\sqrt{K}}{A} m_i \sum_j^m m_j, \]

to be compared with the expression\(^1\)

\[ w_e = \frac{2A^*}{D^*} m_i \sum_j^m \left( \frac{\delta_0}{\pi D} \right) \frac{A^*}{A} \frac{2\sqrt{K}}{D} m_i \sum_j^m m_j, \]

where \( A^* \ll A \) is a phenomenological exchange parameter intended to account for imperfect contact between grains. The second equality displays the relationship between the two formulations. The quantity \( A^*/A \) can be considered equivalent to the fraction \( f \); the ratio \( \delta_0/\pi D \), which is the factor by which the expressions differ, may be expected to be rather smaller than unity. The comparison suggests that the dependence of the exchange energy on grain size may not be correctly predicted by the formulation in Ref. 1, and that it tends to underestimate the exchange interaction.

This is not implausible, since it neglects the anisotropy energy associated with the exchange coupling, and it reduces the estimate of the exchange energy by extending the spin rotation over a range wider than a wall thickness.

This work was supported by the National Science Foundation under Grant No. ECS91-00157.

