by him indicate that this effect may in fact resolve the remaining discrepancy.

(e) Finally, since the disagreement with experiment is only 50%, one should perhaps reconsider refining the calculation of the dipole-dipole interaction which according to Yosida and Tachiki[8] gives in $MnFe_2O_4$ a value of K_1 approximately 10% of the observed anisotropy.

In conclusion although there is a 50% disagreement between the observed and calculated anisotropy of YIG at $T=0°K$, using the crystal field parameters of YGaG, we feel that the major portion of the anisotropy in cubic ferrimagnets arises from the cubic crystal field splittings and that the remaining discrepancy could be explained by any one or combination of items (a) to (e).

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Sputtering of Silicon with A^{+2} Ions

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A gravimetric technique involving a sensitive quartz microbalance was used for the determination of sputtering yields for the argon ion-bombardment of silicon. The sputtering yield for A^{+2} ions was deduced from the results of experiments in which the relative concentrations of A^+ and A^{+2} ions were varied in a known manner. On the assumption that sputtering is a kinetic-energy-controlled phenomenon, we would expect $S_E(A^{+2})=S_{2E}(A^+)$, where S is the number of atoms sputtered by an impinging ion of energy E. This investigation showed, however, that $S_E(A^{+2})\simeq 4S_{2E}(A^+)$. This indicates the influence in the sputtering process of some other factor in addition to the ion kinetic energy.

AN investigation of the sputtering of silicon with argon ions has provided information of the relative effectiveness of singly and doubly charged ions in the sputtering process. The presence of doubly charged ions in the discharge used for sputtering measurements has been found to have caused an overestimation of low-energy sputtering yields.[1] In this work a gravimetric technique involving a sensitive quartz microbalance in ultrahigh vacuum was used for *in situ* measurement of sputtering yields. Weight changes of 0.13 μg (equivalent to 10^{15} silicon atoms) with a maximum deviation of ± 0.06 μg were detectable. The vacuum microbalance apparatus and its application to sputtering studies has been described in other publications.[2,3] The experimental procedure consisted essentially of the measurement of a weight change produced by bombardment of a sample with ions extracted from a thermionically supported low pressure discharge. Argon pressures were 5×10^{-4} to 10^{-3} mm Hg. Discharge conditions were such that the ion energies were well defined and ion incidence was predominantly normal to the target surface. A plasma potential of -4 volts (with respect to ground) has been determined from probe measurements.[2] Current densities of 1 to 17 $\mu a/cm^2$ were employed, with a total of 10^{16} to 10^{19} ions being involved in any one experiment. The samples were high-purity oxygen-free (111)-oriented single-crystal slices, 0.05–0.1 mm thick, with total surface areas of 7–10 cm^2.

Figure 1 presents the sputtering yield, $[S/(1+\gamma^*)]$, as a function of the sample voltage for the argon ion bombardment of silicon at three different discharge voltages (DV). S is the number of atoms sputtered per impinging ion, and γ^* is a generalized correction factor applied to the charge count to yield the number of ions actually involved in the bombardment. For discharges having only singly charged ions, $\gamma^*=\gamma$, the ordinary secondary emission coefficient. For discharges having multiple charged ions, γ^* will contain corrections due to the secondary emission coefficient of the various species and to the multiple charges on some of the ions. At DV = 35–40, only A^+ are present[4] and $S/(1+\gamma^*)=S/(1+\gamma)$. The true ion energies are equal to the sample voltage less the plasma potential. The most interesting feature of these data, as far as this discussion

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is concerned, is the apparent effect of the discharge voltage on the sputtering. Variations of the discharge voltage affect the bombardment only through changes in the relative concentrations of A^+ and A^{+2} ions in the plasma. The plot of Fig. 1 reveals an apparent relationship between the sputtering yield and the concentration of A^{+2} ions in the discharge. As will be shown, the observed data for the mixed discharge cannot be accounted for by the difference in $\gamma(A^+)$ and $\gamma(A^{+2})$.

From an analysis of the data at the three discharge voltages, it has been possible to determine the sputtering yield of A^{+2} ions. The DV=35–40 volt curve was considered to represent the yield for a pure A^+ discharge. The contribution of A^{+3} ions even at DV=150 volts was not considered since they are present to $<1\%$ of the total ion concentration. The relative concentrations of A^+ and A^{+2} ions in the discharge were assumed to be equivalent to those observed by others[4] at similar ionizing electron energies. $\gamma(A^+)$ for bombardment of silicon has been measured by Hagstrum.[5] Although $\gamma(A^{+2})$ has not been experimentally determined, an examination of the data for noble gas ion bombardment of molybdenum[6] and tungsten[7] led us to assume $\gamma(A^{+2}) = 3\gamma(A^+)$. With the above information, the measured total charge was corrected for the presence of A^{+2} ions in the discharge and for the secondary emission contribution. If we assume, as have others,[1,8] the sputtering is primarily a kinetic energy controlled phenomenon, the sputtering yield of a doubly charged ion should be equivalent to that of a singly charged ion at twice the ion energy. The calculated yield for the A^{+2} ion was found to be approximately four times that predicted from kinetic energy considerations, i.e., $S_E(A^{+2}) \simeq 4_{2E}S(A^+)$, where E is the ion energy.

The experimental evidence indicates a surprising effectiveness of the A^{+2} ions in sputtering silicon. Differences between data obtained for the low-energy bombardment of germanium in earlier studies and those of others[9] may possibly be attributed to the higher discharge voltage (DV=275) of our experiments. Other investigators[8] have observed sputtering rates for ionized species to be greater than those for neutral atoms. A consideration of the neutralization energy in addition to the kinetic energy of the impinging ion provides an adequate explanation of the variances in the threshold data of some workers.[8] An additional energy increment due to neutralization, however, is completely inadequate in accounting for the high sputtering yield of the A^{+2} ion.

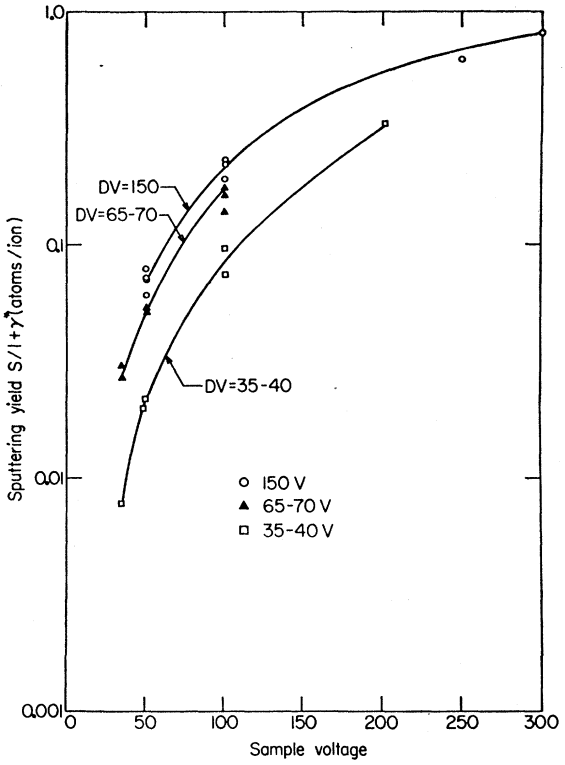

FIG. 1. Argon ion bombardment of silicon [(111), oxygen-free] in the low-energy region.

It can be concluded from this work that the sputtering of silicon with A^{+2} ions involves some other factor in addition to the kinetic energy of the impinging ion. This result is of considerable significance to those investigating the various aspects of the sputtering process.

A detailed discussion of the argon ion-silicon system over a wide energy range along with other sputtering results will be published at a later date.

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