The Interaction of Surface Magnetostatic Waves with Drifting Carriers in Semiconductors

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Abstract—**Characteristics of surface magnetostatic waves (SMW) propagating in the direction perpendicular to an external dc magnetic field and interacting with drifting carriers in semiconductors were studied. Loss of the waves was observed to be decreased due to the interaction with drifting carriers even if the drift velocity of carriers did not exceed the phase velocity of the waves.**

INTRODUCTION

IT IS IMPORTANT to be able to obtain amplification of magnetostatic waves due to the interaction with drifting carriers in order to compensate for propagation loss and conversion loss in delay lines using magnetostatic waves. Interaction of volume magnetostatic waves (VMW) propagating in the direction of an external dc magnetic field is not suitable because the beam flux of the waves becomes concentrated at the center of a rod and the interaction with drifting carriers at the rod boundary is quite weak for short wavelengths due to the focusing effect of the VMW. Furthermore, it is difficult to obtain a high gain since with surface magnetostatic waves (SMW) short-wavelength waves are not allowed due to the existence of a cutoff.

For ferrimagnetic semiconductors, small values in the product of resistivity and linewidth are needed, so it is impossible to obtain a growing wave interaction with the available material [1]. Schlömann and Vural have given numerical examples of the interactions of SMW propagating perpendicular to the external dc magnetic field with drifting carriers in semiconductors [1], [2]. But very few experimental observations are reported.

The change of the internal dc magnetic field caused by the pulse current flowing through the semiconductor plate was not taken into account in Vural's and Vashkovskii's experiments. Only the variations of transmitted power were measured with and without dc pulses, and the delay characteristics were not reported in Vural's experiment [3]. Gains of SMW due to the interaction were underestimated in Vashkovskii's experiment [4].

In this paper, the dispersion relations of SMW interacting with drifting carriers in semiconductors are analytically studied. Furthermore, it was experimentally observed that the transmitted power of SMW increases with increasing electric field applied to the semiconductor. Also the influence of conduction loss on the propagation characteristics was examined by changing the resistivity of the semiconductor. Gain was observed due to interaction with holes in p-type Ge.

Manuscript received April 1, 1974; revised July 9, 1974.
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THEORY

We assume a YIG slab of thickness a is placed on a metal plate, and a semiconducting plate of thickness c is placed in contact with the YIG surface, as shown in Fig. 1. The waves are considered to propagate along the $\pm y$ directions and the external dc magnetic field is taken to be along the z direction. The direction of carrier motion is in the $+y$ direction. The z dependence of the waves is neglected to simplify analysis. This is a reasonable assumption for waves with very large wavenumber k. Since the current component J_z is important, TE modes with the components of E_z, H_x, and H_y only are assumed. From Maxwell's equations and the equations of the motion of the carriers, the dispersion relation is derived as follows.

The electric field E_z is expressed in the YIG slab as

$$E_z = \{A_1 \exp(-\gamma_f x) + A_2 \exp(\gamma_f x)\} \cdot \exp i(\omega t \mp ky), \qquad -a < x < 0$$

in the semiconducting plate as

$$E_z = \{A_3 \exp(-\gamma_s x) + A_4 \exp(\gamma_s x)\} \cdot \exp i(\omega t \mp ky), \quad 0 < x < c$$

and in the dielectric as

$$E_z = A_5 \exp(-\gamma_d x) \cdot \exp i(\omega t \mp ky), \qquad c < x. \quad (1)$$

Magnetostatic approximations hold for the waves with large k so the following relations are satisfied:

$$\gamma_f^2 = \gamma_d^2 = k^2. \quad (2)$$

For γ_s, the following expression can be derived

$$\gamma_s^2 = k^2 - \frac{\omega^2}{c_s^2}\left(1 - \frac{\omega_p^2}{\omega^2}\frac{\omega \mp kv_0}{\omega \mp kv_0 - i\nu}\right) \quad (3)$$

where $\omega_p^2 = q^2 n / m\epsilon_0\epsilon_s$ and $c_s^2 = 1/\mu_0\epsilon_0\epsilon_s$, and n, m, q, and ν are the concentration, effective mass, electric charge, and the collision frequency of carriers, and ϵ_s is the relative dielectric constant of semiconductor. From the boundary conditions that the normal component of magnetic flux density must vanish on the metal surface at $x = -a$ and the tangential components of magnetic field and the normal components of magnetic flux density must be continuous on the boundaries at $x = 0$ and $x = c$, the following transcendental equation is obtained:

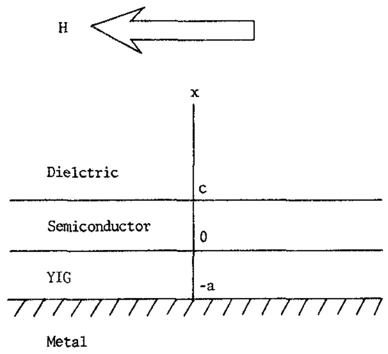

Fig. 1. Coordinate system.

$$\exp(ka)\left\{\left(\frac{k}{\mu\pm\kappa}+\gamma_s\right)(k+\gamma_s)\cdot\exp(\gamma_s c)-\left(\frac{k}{\mu\pm\kappa}-\gamma_s\right)(k-\gamma_s)\cdot\exp(-\gamma_s c)\right\}$$
$$-\exp(-ka)\left\{\left(-\frac{k}{\mu\mp\kappa}+\gamma_s\right)(k+\gamma_s)\cdot\exp(\gamma_s c)+\left(\frac{k}{\mu\mp\kappa}+\gamma_s\right)(k-\gamma_s)\cdot\exp(-\gamma_s c)\right\}=0 \quad (4)$$

where μ and κ are the diagonal and off-diagonal elements of the permeability tensor. Let us first consider that the semiconductor plate is replaced with a dielectric. Then, from (3), $\gamma_s\rightarrow k$ is obtained for $\omega_p\rightarrow 0$. In the limit of $c\rightarrow\infty$, (4) is simplified as follows:

$$\tanh ka=\frac{\mu}{-\mu^2+\kappa^2\pm\kappa} \quad (5)$$

which is the dispersion relation of SMW with the z dependence of the waves neglected. The passband lies between the limits $k\rightarrow 0$ and $k\rightarrow\infty$ in (5) and is expressed as follows:

$$[\omega_0(\omega_0+\omega_M)]^{1/2}<\omega<\omega_0+\omega_M/2, \qquad \text{for } +y \text{ directed SMW}$$
$$[\omega_0(\omega_0+\omega_M)]^{1/2}<\omega<\omega_0+\omega_M, \qquad \text{for } -y \text{ directed SMW.} \quad (6)$$

In (6), ω_0 is the precessional angular frequency and ω_M is the angular frequency of saturation magnetization. SMW propagating along the metal-bounded surface ($-y$ direction) and along the free surface ($+y$ direction) are known as ferrite–metal (FM) and ferrite–air (FA) modes. Nonreciprocal transmission of SMW has already been demonstrated [5].

Let us secondly consider SMW interacting with drifting carriers in semiconductors when the direction of propagation of SMW is in the $+y$ direction. Our analysis is confined to the collision dominant case: $\nu\gg\omega$, kv_0, and $|\omega_p^2(\omega-kv_0)/\omega^2\nu|\gg 1$. Then from (3)

$$\gamma_s^2=k^2+\sigma\mu_0(\omega-kv_0)i$$

is obtained, where σ is the conductivity. Furthermore, it is assumed that

$$|k^2|\gg|\sigma\mu_0(\omega-kv_0)|. \quad (7)$$

Then the following expression for the transverse propagation constant γ_s is obtained:

$$\gamma_s=k\left\{1+\frac{\sigma\mu_0(\omega-kv_0)}{2k^2}i\right\}. \quad (8)$$

It is assumed that the thicknesses of the YIG slab and the semiconductor plate are much longer than the wavelength: $ka\gg 1$, $\gamma_s c\gg 1$. Then (4) may be simplified as follows:

$$\left(\gamma_s+\frac{k}{\mu+\kappa}\right)\cdot(\gamma_s+k)=0. \quad (9)$$

The first factor of (9) is of interest. From (8) and (9), a quadratic equation for k is obtained

$$2\left(\frac{1}{\mu+\kappa}+1\right)k^2-\sigma\mu_0v_0ki+\sigma\mu_0\omega i=0. \quad (10)$$

For simplicity we put

$$\frac{1}{\mu+\kappa}+1=\frac{\omega_0-\omega+\omega_M/2}{2(\omega_0-\omega+\omega_M)}=X. \quad (11)$$

With the assumption

$$|\sigma\mu_0v_0^2|>|8\omega X| \quad (12)$$

the two solutions of (10) become

$$k_1=-\frac{\omega}{v_0}+\frac{\sigma\mu_0v_0}{2X}i$$

$$k_2=\frac{\omega}{v_0}. \quad (13)$$

The solution of interest is the k_1 mode. The k_1 mode is a backward wave, since real (k_1) is negative for a positive value of v_0. In order to obtain a high gain, the imaginary part of k_1 must be negative and large, and so high conductivity, fast drift velocity, or a small negative value of X are needed. Negative small value of X means $\omega=\omega_0+\omega_M/2+\delta\omega$, $\omega_0+\omega_M/2\gg\delta\omega>0$, which indicates the widening of passband of propagation. This fact seems to be caused by the strong metallic property of semiconductor on the assumption of inequality (12).

Next consider an assumption opposite to inequality (12)

$$|\sigma\mu_0v_0^2|<|8\omega X|. \quad (14)$$

Then the two solutions of (10) are expressed as

$$k_3=\left\{2(\sigma\mu_0\omega X)^{1/2}-\frac{(\sigma\mu_0)^{3/2}v_0^2}{8(\omega X)^{1/2}}+i\left(\sigma\mu_0v_0-2(\sigma\mu_0\omega X)^{1/2}-\frac{(\sigma\mu_0)^{3/2}v_0^2}{8(\omega X)^{1/2}}\right)\right\}\Big/4X$$

$$k_4 = \left\{\frac{(\sigma\mu_0)^{3/2}v_0^2}{8(\omega X)^{1/2}} - 2(\sigma\mu_0\omega X)^{1/2} + i\left(\sigma\mu_0 v_0 + 2(\sigma\mu_0\omega X)^{1/2} + \frac{(\sigma\mu_0)^{3/2}v_0^2}{8(\omega X)^{1/2}}\right)\right\} \Big/ 4X. \quad (15)$$

The solution of interest is the k_3 mode. The second term of the imaginary part of k_3 is caused by the conduction loss inside the semiconductor. On the assumption of inequality (14), the following expression holds:

$$2(\sigma\mu_0\omega X)^{1/2} > |\sigma\mu_0 v_0| > (\sigma\mu_0)^{3/2}v_0^2/8(\omega X)^{1/2}. \quad (16)$$

Hence the k_3 mode is heavily damped and the growth rate of the waves is given by $\sigma\mu_0 v_0/4X$ to a first approximation. In order to obtain a high gain, high conductivity, fast drift velocity, or a small positive value of X are needed on the assumption of inequality (14). A positive small value of X means $\omega = \omega_0 + \omega_M/2 - \delta\omega$, $\omega_0 + \omega_M/2 \gg \delta\omega > 0$, which indicates that the waves must be at a high k state and that the widening of the passband of propagation does not occur.

As may be seen from (13) and (15), the growth rate of the waves is given by a linear function of the drift velocity. This nature of the waves is generally proved by Brigg's electrokinetic-power theorem for the TE modes under consideration [6]. Recently, computer-aided results of the complex dispersion relation of (4) have been shown and a linear gain–loss characteristic is obtained as a function of the drift velocity of mobile carriers [7].

EXPERIMENTAL PROCEDURES

Our sample was a single crystal of Ga-substituted YIG with saturation magnetization of 1200 G and linewidth to be less than 0.5 Oe. It had dimensions of 0.925 × 5.2 × 18.2 mm^3 and the surfaces along which SMW propagate were polished optically flat. Microwave power from a klystron was applied to a thin wire antenna near the slab end. The detection antenna was located near the opposite end of the slab. These antennas were parallel to the external dc magnetic field and had short-circuit ends. The driving power was limited to be less than 0.1 mW to avoid saturation effects and instabilities for the measurement without a semiconductor plate in contact with the YIG slab [8].

The transmitted microwave power or reflected power through a circulator was rectified by a diode 1N23B and applied to a Y input of an X–Y recorder. The X input was the sweep voltage for dc magnetic field. We have determined the modes of propagating SMW from the spectrum of transmitted or reflected microwave power versus internal dc magnetic-field strength.

For the measurement of time delays, microwave power was applied, which was pulse modulated with a p-i-n diode switch. Delayed signals were mixed with a local oscillation signal, amplified through a wide-band amplifier, rectified, and displayed on a dual-beam oscilloscope.

To examine the effect of conduction (joule) loss on the propagation characteristics, semiconductor plates having resistivities of 0.03, 0.1, 1.0, 10, and 30 Ω·cm were prepared. These plates had the same dimensions as the YIG slab except that the thickness was 0.3 mm. Conduction loss for SMW is a function of the wavelength, thicknesses of the YIG slab and the semiconductor plate, and the resistivity. The wavelength giving the maximum attenuation varies with the value of resistivity [9]. Transmitted power decreased considerably when the semiconductor plate was placed in contact with the surface of the YIG slab.

Ohmic contacts were made on the end edges of the semiconductor plate thus avoiding a change of resistivity due to the injection of minority carriers. The sample which showed a relatively good I–V characteristic was a single crystal of p-Ge. It had dimensions of 0.38 × 1.70 × 8.0 mm^3 and resistivity of 3.2 Ω·cm, and the hole mobility was 1800 cm^2/V·s. The contacting wide surface was also polished optically flat. After the mechanical polish, ohmic contacts were made from small tips of InGa by the alloy method. The surface layers containing the impurities evaporated through the alloying were removed by a chemical etching and the sample was washed in ethyl alcohol of high purity. To guard the sample from oxidation, the semiconductor plate was placed in contact with the YIG plate and experiments were performed soon after the drying of the sample.

To prevent the sample from heating, the repetition rate of the dc pulse applied to the semiconductor was held at 15 Hz. The pulse had a width of 1.2 μs, and the rise and fall times were 0.05 and 0.2 μs, respectively. The pulser used in our experiment was a Velonex Model 350. Microwave power was pulse-modulated by a short pulse of width 0.2 μs. The two pulses were triggered by the same trigger signal but the trigger applied to a p-i-n diode switch driver was fed through a variable delay circuit. Hence the relative time difference between the two pulses were selected freely.

All the experiments were performed at S band 4.143 GHz at room temperature. The semiconductor plate was placed at the center of the surface of the YIG slab and slightly pressed onto the YIG slab by a thin Teflon screw in order to obtain uniform contacts in the boundary planes.

EXPERIMENTAL RESULTS AND DISCUSSION

An expression for the group velocity of the waves including the z dependence and the slab thickness is difficult to obtain. The solution may be simplified by neglecting the slab thickness and assuming that the waves propagate along the surface of a semiinfinite slab. This is justified since, for the waves with large k, the magnetic potential decays rapidly from the surface along which the wave is propagating. The effect of the finite boundaries of a slab is included through the demagnetizing field [8]. In Fig. 2, theoretical and experimental delay times are shown as a function of the internal dc magnetic-field strength. Agreement with theory is good if the loss inside the ferrite is taken into account. The z dependence of the waves is given by $k_z = n\pi/b$ with $n = 1$, where b is the width of the YIG slab. In Fig. 3, typical waveforms of the delayed signals are shown. Multiple echoes were observed for short

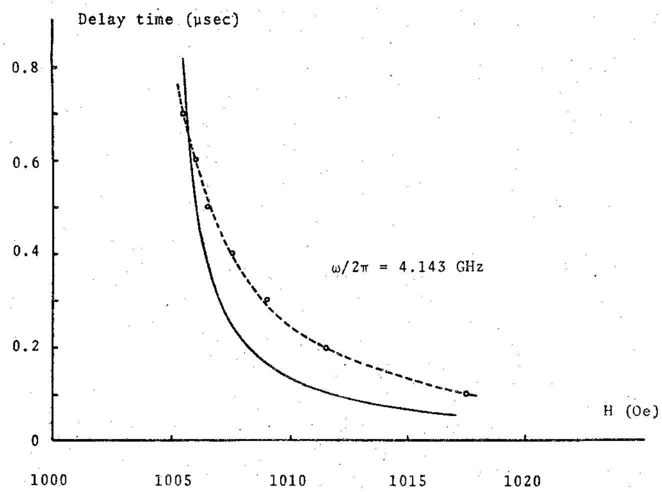

Fig. 2. Delay time as a function of the internal dc magnetic-field strength. Theoretical curve (solid line); experimental curve (broken line).

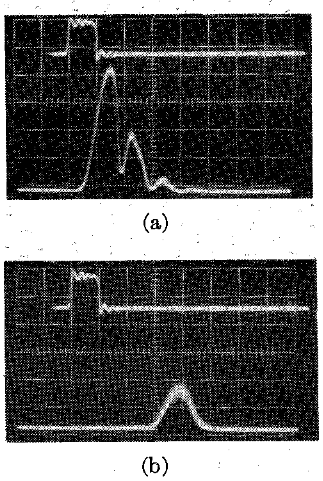

Fig. 3. Waveforms of delayed signals. The upper trace is the rectangular pulse which turns on a p-i-n diode switch. The lower trace is the delayed signals. Horizontal axis: 0.2 μs/div; vertical axis: 5 V/div and 20 mV/div for (a) and 5 mV/div for (b).

delay times, and the length of the delayed pulse was found to increase for longer delay times.

In Fig. 4, attenuation characteristics of SMW are shown. From an attenuation rate per unit delay time, the linewidth for SMW is estimated to be $\Delta H = 0.7$ Oe and it is larger than that observed for VMW. A remarkable decrease of transmitted power and widening of the linewidth in the spectrum occurred when the semiconductor plate was placed in contact with the YIG surface. The same phenomena were also observed for VMW. But the effect was much smaller in that case. The maximum attenuation was observed for a resistivity of 1.0 $\Omega\cdot$cm by the measurement of transmitted power by an X–Y recorder. Considering the limits of $\sigma \rightarrow \infty$ and $\sigma \rightarrow 0$, due to a shield effect of a perfect metal for the former and no current flowing for the latter, conduction loss may be negligible for both cases. Hence the conduction loss has a maximum for a certain finite value of conductivity.

Widening of the passband of propagation for the $+y$-directed SMW occurred for resistivity below 0.1 $\Omega\cdot$cm;

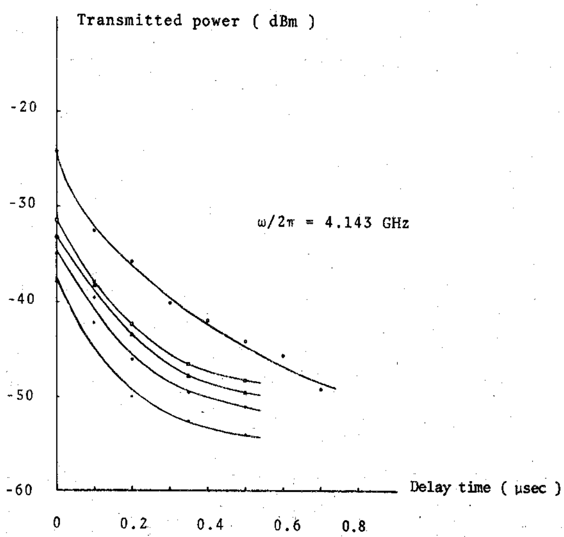

Fig. 4. Attenuation characteristics of surface magnetostatic waves. The experimental curves are obtained, from the top to the bottom, for the $+y$-directed FA mode and for SMW with inclusion of a semiconductor plate: the applied electric-field strength is 2, 1, 0, and -2 kV/cm in order. Applied microwave power to the specimen is -15.1 dBm for the upper curve and 4.9 dBm for the rest.

that is, the lower cutoff dc magnetic-field strength has a lower value than $H = \omega_0/\gamma = (\omega - \omega_M/2)/\gamma$. A qualitative explanation of the effect may be given by considering the strong metallic property of the semiconductor for low resistivity. The same explanation is applicable for the passband widening of SMW when a perfect metal is brought near the YIG surface. A description of passband control of the SMW has already been published for situations when: a) the direction of propagation is parallel to the external dc magnetic field [10], and b) it is perpendicular to the external dc magnetic field [11], [12].

In Fig. 4, the delay characteristics of the SMW are also shown when the semiconductor plate was introduced and an electric field was applied. Introduction of the semiconductor plate brought about a decrease of transmitted power by 25 $\sim$ 30 dB, and so the driving power was increased by 20 dB compared with the measurement without a semiconductor plate. Transmitted power increased when the holes drift in the direction of propagation of SMW and decreased when the holes drift in the opposite direction.

In Fig. 5, curves of electronic gain are shown as a function of the applied electric-field strength with delay time as a parameter. Electronic gain is defined as $10 \log (P_2/P_1)$, where P_2 and P_1 are the transmitted powers with and without the dc pulses, respectively. It is seen that the transmitted power increases approximately linearly with increasing electric field and decreases for the change of the polarity of the electric field as the theory predicts. Increase of transmitted power was 3 dB when an electric-field strength of 2 kV/cm was applied to the specimen with a delay time of 0.5 μs. The interaction was strongly influenced by the state of the surface and the contact between the YIG slab and the semiconductor plate. The experimental values are poorly reproducible at the present time. Typical oscilloscope traces of the delayed signals

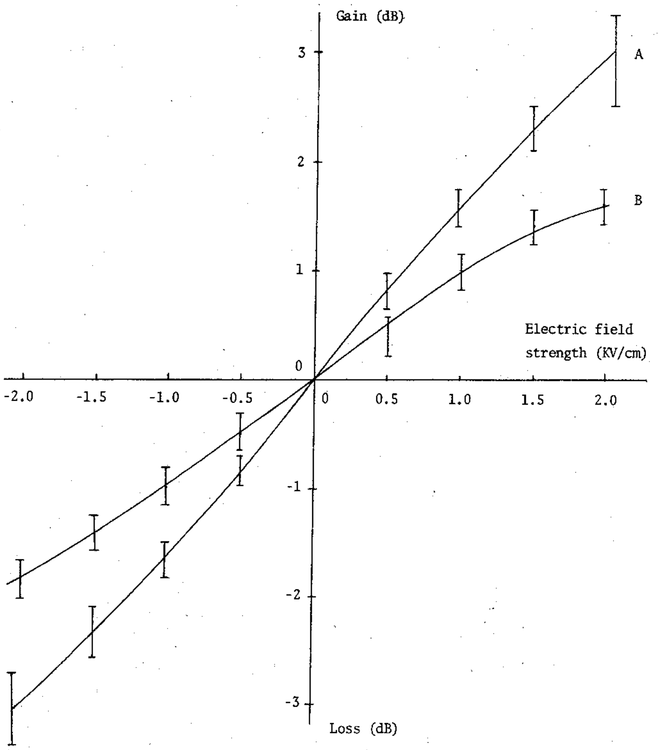

Fig. 5. Gain–loss characteristics as a function of applied electric-field strength. Delay times are 0.1 and 0.5 μs for A and B, respectively.

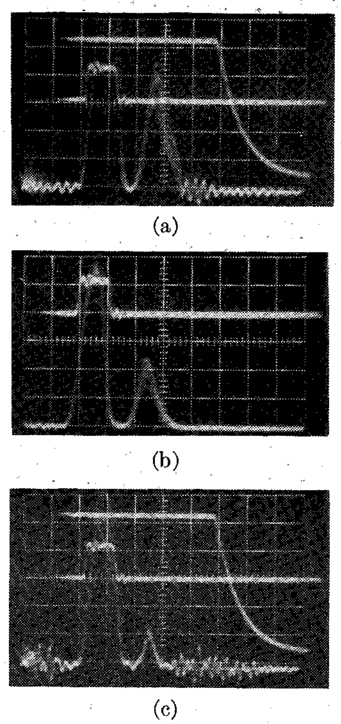

Fig. 6. Variations of transmitted power of SMW interacting with drifting carriers in semiconductor. The upper trace is a drift pulse, the middle trace is the rectangular pulse which turns on a p-i-n diode switch, and the lower trace consists of a direct leakage signal and a delayed signal. The drift fields are 1, 0, and −1 kV for (a), (b), and (c), respectively. Horizontal axis: 0.2 μs/div; vertical axis: 200 V, 5 V, and 5 mV/div, respectively.

interacting with the mobile carriers in semiconductors are shown in Fig. 6. The increase and decrease of the transmitted power are obvious over that of a signal without the drift pulse present. Due to the large dielectric constant of Ge and the increase of driving power, direct leakage signals are also observed without time delays.

In Fig. 7, delay times are shown as a function of the external dc magnetic-field strength with applied electric-field strength as a parameter. Due to the pulse current flowing through the semiconductor plate, the internal dc magnetic-field strength near the surface of the YIG slab increases and the delay time is shortened if the external dc magnetic field is kept constant for the parallel propagation of the wave vector $\boldsymbol{k}$ and the carrier drift motion $\boldsymbol{v}_0$. Small decline of delay times with the introduction of a semiconductor plate indicates the increase of loss due to the conduction mechanism inside the semiconductor, compared with the sharp decline without a semiconductor plate.

In Fig. 8, the I–V characteristic of the semiconductor used in our experiments is shown. The I–V curve departs from an ohmic line for the electric-field strength above 1 kV/cm and the increase of resistance begins due to the decreasing of mobility. Decreasing of mobility at high electric field seems to be brought about by the alloying at high temperature (500°C, 10 min). It was confirmed that the injection of minority carriers does not occur by comparing the waveforms of voltage and current pulses on an oscilloscope. The same I–V curve was obtained for the change of polarity of the dc pulse.

To confirm the interaction of SMW with drifting carriers, a copper plate having the same dimension as the p-Ge plate was used in the place of semiconductor and dc pulse was applied. Delay times varied due to the change of the internal dc magnetic field, but the amplitudes of transmitted power did not change if the external dc magnetic field was adjusted so as to give the same delay times and the conduction loss was much smaller in this case. This was true for the parallel and antiparallel current flowing of $\boldsymbol{I}$ with $\boldsymbol{k}$. If mobile carriers are electrons, the

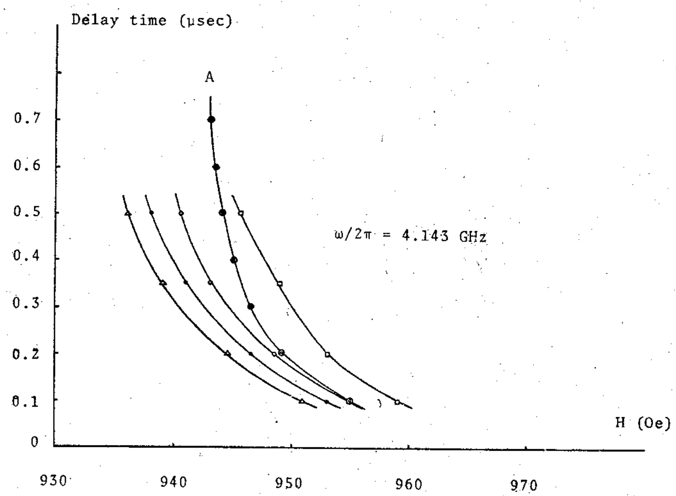

Fig. 7. Delay time as a function of the external dc magnetic-field strength. The curve A is obtained for the $+y$-directed FA mode and the rest are obtained with the inclusion of a semiconductor plate. The applied electric-field strengths are, from the left to the right, 2, 1, 0, and −2 kV/cm, respectively.

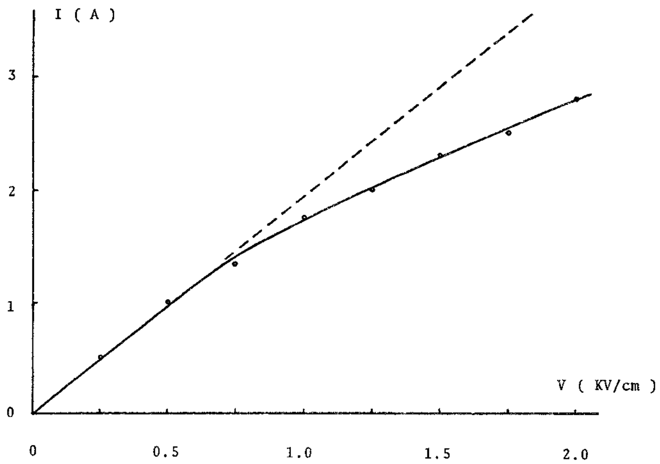

Fig. 8. *I–V* characteristics of the semiconductor. The external dc magnetic-field strength is 940 Oe. Magnetoresistance is small for this specimen and the same *I–V* curve was obtained with zero magnetic field.

change of the internal dc magnetic field is opposite to flowing of $\boldsymbol{I}$ with $\boldsymbol{k}$. If mobile carriers are electrons, the change of the internal dc magnetic field is opposite to that for holes. Hence electronic gain must be larger than the value reported by Vashkovskii [4].

Amplification and attenuation were observed depending on the instant of time of the wave propagation at which the drift field is applied to the semiconductor in Vashkovskii's experiments. In our experiments, however, transmitted power was constant within the flat region of the drift pulse (approximately two-thirds of the pulsewidth from the leading edge) except near the trailing edge. The delay characteristics obtained by removing the pulse of SMW far away from the drift pulse were the same as those obtained by setting the drift-field zero. Hence the heating effect of the sample may be ignored.

The wavenumber k has a maximum of 100 cm^{-1} for a magnetostatic delay of 1.7 μs even if the ferrite has no losses ($\Delta H = 0$), and the phase velocity is much greater than the drift velocity of the holes. The assumption of (7) is easily satisfied for the parameters of $\sigma = 3.1 \times 10^1$ $\mho \cdot m$, $v_0 = 3.6 \times 10^4$ m/s, $\omega/2\pi = 4.143$ GHz, and $k = 10^4$ m^{-1}. For relatively slow drift velocity, a very small value of X is needed in order to satisfy the condition (12). Hence the assumption of condition (14) is noted. Then from (15), the conduction loss and the electronic gain are calculated to be 1.6×10^2 cm^{-1} and 3.6 cm^{-1}, respectively, for the choice of $X = 10^{-3}$. The experimental values of these quantities are estimated to be 4.5 cm^{-1} and 0.44 cm^{-1}, respectively, for a delay time of 0.5 μs. The discrepancy of the theoretical and the experimental values may be caused partly by an imperfect contact between the YIG slab and the semiconductor plate and partly by the presence of surface states of semiconductors.

CONCLUSION

Propagation loss due to the conduction loss inside the semiconductor was measured as a function of resistivity. The loss has a maximum for a certain finite value of resistivity. To obtain as high a carrier drift velocity as possible, semiconductors with high resistivity are preferable. But the interaction may be stronger for a large number of mobile carriers. Hence a thin film with high mobility and low resistivity is most preferable for the semiconductor material.

The interaction of SMW with drifting carriers in semiconductors was measured taking into account the change of the internal dc magnetic field caused by the pulse current. Decrease of loss of SMW was observed due to the interaction with drifting carriers even if the drift velocity of mobile carriers did not exceed the phase velocity.

In order to obtain high gain for relatively small drift velocity, the phase velocity must be small. This means that the wavenumber k must be large and thus

$$\omega_0 \cong \omega - \omega_M/2$$

must be satisfied. Hence an amplifier of this type is essentially narrow band: for instance $| \omega_0 - (\omega - \omega_M/2) |/\gamma$ is less than 0.5 Oe. The exact gain must be calculated taking into account the velocity distribution of carriers and the z dependence of the waves.

As the theory predicts, the electronic gain is quite large for high velocity. In order for net amplification to occur, however, quite high drift velocity such as 10^8 cm/s is needed, as is often quoted in the papers. This is a severe criterion for semiconductors. Only the electrons in n-type InSb could satisfy this criterion.

Application of electric-field strength above 2 kV/cm to Ge brings about the existence of hot carriers and the drift velocity begins to saturate. Furthermore, semiconductor specimens without the injection of minority carriers are difficult to make. The injection of minority carriers reduces the electronic gain calculated from the theory depending on the degree of injection.

There remain some other problems such as the imperfectness of the contact between the ferrite and semiconductor plates and the presence of surface states of the specimens. The most significant problem is the presence of surface state of semiconductors. Another type of mobile carriers different from that of the material exists near the surface when the surface state is present. Furthermore, it remains always as a question whether the mobile carriers near the surface can drift as fast as drifting in the bulk of the semiconductor.

ACKNOWLEDGMENT

The authors wish to thank Prof. S. Miki at the Science University of Tokyo and Prof. Y. Amemiya at Nagoya University for their earnest and kind suggestions during the course of these investigations.

REFERENCES

[1] B. B. Robinson, B. Vural, and J. P. Parekh, "Spin-wave/carrier-wave interactions," *IEEE Trans. Electron Devices* (*Special Issue on Wave Interactions in Solids*), vol. ED-17, pp. 224–229, Mar. 1970.
[2] E. Schlömann, "Amplification of magnetostatic surface wave by interaction with drifting charge carriers in crossed electric and magnetic field," *J. Appl. Phys.*, vol. 40, p. 1422, 1969.
[3] M. C. Steel and B. Vural, *Wave Interactions in Solid State*

Plasmas. New York: McGraw-Hill, 1969.
[4] A. V. Vashkovskii *et al.*, "Interaction of surface magnetostatic waves with carriers on a ferrite-semiconductor interface," *Sov. Phys.—JETP Lett.*, vol. 16, p. 4, 1972.
[5] G. A. Benett and J. D. Adam, "Identification of surface wave resonances on a metal backed YIG slab," *Electron. Lett.*, vol. 6, p. 789, 1970.
[6] R. J. Briggs, *Electron-Stream Interaction with Plasmas.* Cambridge, Mass.: M.I.T. Press, 1964.
[7] K. Ohtsuki *et al.*, private communication.
[8] J. D. Adam, "Delay of magnetostatic surface waves in YIG," *Electron. Lett.*, vol. 6, p. 718, 1970.
[9] R. E. de Wames and T. Wolfram, "Characteristics of magnetostatic surface waves for a metalized ferrite slab," *J. Appl. Phys.*, vol. 41, p. 5243, 1970.
[10] K. Kawasaki and M. Umeno, "Influence of surface metallization on the propagation characteristics of surface magnetostatic waves in an axially magnetized rectangular YIG rod," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 391–394, Apr. 1974.
[11] H. Van de Vaart, "Influence of metal plate on the surface magnetostatic modes of magnetic slab," *Electron. Lett.*, vol. 6, p. 601, 1970.
[12] K. Kawasaki, H. Takagi, and M. Umeno, "Passband control of surface magnetostatic waves by spacing a metal plate apart from the ferrite surface," this issue, pp. 924–929.

Passband Control of Surface Magnetostatic Waves by Spacing a Metal Plate Apart from the Ferrite Surface

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Abstract—**The effect of a metal plate on the propagation characteristics of surface magnetostatic waves (SMW) propagating perpendicular to an external dc magnetic field was studied by varying the spacing of the metal plate from the ferrite surface. Continuous passband control is obtained by changing the spacing from zero to infinity and the existence of a partial stopband for the interchange of the input and output ports is also obtained in addition to the disappearance of nonreciprocal propagation for a finite spacing of the metal plate.**

INTRODUCTION

MUCH EFFORT has recently been devoted to the study of surface magnetostatic waves (SMW) with the development of magnetic thin films of high quality. SMW propagating perpendicular to an external dc magnetic field have strong nonreciprocity depending on the direction of propagation. SMW which propagate along the metal-bounded surface and along the free surface are known as a ferrite-metal (FM) and as a ferrite-air (FA) mode, and their passbands are from

$$\omega = [\omega_0(\omega_0 + \omega_M)]^{1/2} \quad \text{to} \quad \omega = \omega_0 + \omega_M$$

and from $\omega = [\omega_0(\omega_0 + \omega_M)]^{1/2}$ to $\omega = \omega_0 + \omega_M/2$, respectively, where $\omega_0 = \gamma H_0$ is the precession angular frequency and $\omega_M = \gamma 4\pi M$ is the angular frequency of the saturation magnetization. Nonreciprocity of the waves can be used in the application to microwave components [1]–[3].

Van de Vaart has derived the dispersion relations for SMW propagating in a ferrite slab with a conductive plate located at a small distance parallel to the surface of the slab. SMW propagating along the metal-bounded surface in this configuration consist of forward or backward waves depending on the wavelength of the mode and the distance of the conducting plate from the ferrite surface [4]. Bongianni has also derived the same dispersion relations and performed some experiments with a dielectric-layered structure consisting of an epitaxial YIG film separated by a thin dielectric layer. He has reported experimental results mainly concerning the delay characteristics of the waves [5]. The dependence of the waves on the direction of the external dc magnetic field was first introduced by Sparks, and the theoretical results agreed surprisingly well with the Brundle and Freedman experimental values [6], [7].

In a previous paper, we have reported the influence of metal plates on the propagation characteristics of SMW propagating in the direction of the external dc magnetic field, and then proposed a new type of microwave filter which is mechanically tunable [8].

In this paper, we show the continuous passband control of SMW propagating perpendicular to the external dc magnetic field by changing the spacing of the metal plate from the ferrite surface. The same phenomenon occurs for SMW propagating in the direction of the external dc magnetic field. The difference between the two cases is an asymmetrical situation for the metal plate located parallel to the ferrite surface for the former and a symmetrical situation for the metal plates placed parallel to the surfaces for the latter. We show additional features of the waves: the disappearance of nonreciprocity for a finite spacing of the metal plate and the existence of a

Manuscript received March 18, 1974; revised June 26, 1974.
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