A Low-Noise InSb Thin Film Hall Element: Fabrication, Device Modeling, and Audio Application

NOBUO KOTERA, JUNJI SHIGETA, KOZIRO NARITA, TETSU OI, KENJI HAYASHI, AND KIKUJI SATO

Abstract—Low-noise InSb thin film Hall elements have been developed as magnetic sensors for audio tape playback. Approximately 1.4-μm thick Hall elements are fabricated by vacuum deposition followed by microzone melting, film thinning, and subsequent heat treatment. After film thinning, electron mobility at room temperature is 6 m²/V · s showing the 1-ppm level impurity concentration. After heat treatment, noise is at the 0.5-pV level for frequencies in the 10²-10⁴ Hz range and signal-to-noise ratio of the Hall elements is 82 dB in a 1-mT (10-G) magnetic flux density. The device characteristics as functions of dc bias current is successfully computer-simulated, where element Joule heating is taken into account. The calculated results agree quantitatively with the experimental results. In order to apply the Hall elements to audio magnetic heads for cassette tape playing, the head design principle and the head signal-to-noise ratio are clarified for the first time. The advantages of the Hall effect magnetic heads are also discussed.

NOMENCLATURE

- $N$: Noise voltage (rms value) generated between Hall electrodes.
- $A$: Acceptor concentration.
- $C$: Noise voltage (rms value) due to current noise of $1/f$ type spectrum.
- $D$: Donor concentration.
- $I$: Total ionized-impurity concentration.
- $O$: Noise voltage (rms value) due to Johnson noise observed at zero bias current.
- $R_H$: Hall coefficient.
- $S$: Hall voltage.
- $S'/N$: Output voltage of Hall head without equalization.
- $S/N$: Signal-to-noise ratio (SNR) of Hall element.
- $S_H/N_h$: Signal-to-noise ratio (SNR) of Hall head after equalization.
- $T$: Temperature of Hall element.
- $T_i$: Element temperature in the $i$th iterative calculation.
- $T_o$: Temperature of environmental air.
- $W$: Width of Hall element.
- $X$: Process-dependent parameter defining noise intensity coefficient.
- $\alpha$: Heat transfer constant.
- $\delta$: Partial flux coefficient.
- $\gamma$: Scattering factor.
- $\Gamma$: Magnetic flux transfer efficiency from magnetic tape into head gap structure.
- $\phi$: Tape magnetic flux.
- $\phi_0$: Standard tape flux level.
- $\delta_s$: Magnetic flux transfer rate to Hall element in head structure.
- $\mu_H$: Hall mobility, defined experimentally as $R_H/p$.
- $\mu_n$: Electron mobility.
- $\mu_p$: Hole mobility.
- $\rho$: Resistivity.
- $\tau_1$: Time constant for standard tape recording at low frequency.
- $\tau_2$: Time constant for standard tape recording at high frequency.

I. INTRODUCTION

Indium Antimonide (InSb) crystal is one of the best materials for Hall elements because of its high mobility and the resultant high output voltage. For commercial appli-
cations, thin film Hall elements have the advantage of low cost compared with bulk-type Hall elements.

It has been suggested by many workers [1]-[11] that semiconductor Hall elements can be used in place of coils for magnetic tape signal pickup. The Hall effect magnetic heads (Hall heads) are expected to be superior to conventional coil heads in their high and frequency-independent output voltage [9]. However, no commercially available audio Hall heads have been developed before.

For such an application, a Hall element with a semiconductor film about 1 μm thick should be sandwiched between ferrite pole pieces. This is because tape magnetic flux can be introduced more effectively into thinner elements. In addition, the Hall element should have low noise in order to obtain a high signal-to-noise ratio (SNR). So far, however, little effort has been devoted to reducing the noise in such thin InSb films down to the 0.5-μV level. Moreover, the properties of the noise generated between Hall electrodes have not been clarified and the element design theory has never been established, especially for the SNR.

In previous papers [12]-[14], microzone melting of an evaporated InSb film was found useful for reducing the element noise. In another previous paper [15], the 1/f noise generated between Hall electrodes in a zero or small magnetic flux density was analyzed and closely correlated to the number of carriers. Moreover, the formulas for both 1/f noise and Hall element SNR were established.

In this paper, improved fabrication processes of a low-noise InSb thin film Hall element are described first. Second, the electrical transport properties in InSb crystal are calculated as functions of donor and acceptor concentrations for device modeling. The calculation is based on a simple two-band model, the Fermi-Dirac statistics, and the empirical mobility versus impurity concentration curve [16]. Third, the device characteristics, including Hall element SNR, are examined experimentally and calculated theoretically as a function of dc bias current. This calculation agrees quantitatively with experiments and gives an accurate device design theory. In the audio frequency measurement between 10²-10⁴ Hz, the SNR of the 1.4-μm thick Hall elements reached 82 dB in a homogeneous 1-mT (10-G) magnetic flux density, which is sufficient for the Hall element to be applied to audio Hall heads [17], [18]. Finally, the design principle of Hall heads for cassette tape deck is given and the element SNR for the first time. The advantages of audio Hall heads are also discussed.

II. HALL ELEMENT FABRICATION

To facilitate introducing magnetic flux into Hall elements, a sintered Ni-Zn ferrite plate is used for the substrate, as illustrated in Fig. 1. On the 18 mm × 23 mm substrate surface, pure SiO₂ glass of less than 60-ppm impurity is sputtered to a designated thickness. The approximately 1-μm thick sputtered layer is partly removed by a conventional photoetching technique to form approximately 20 grooves in the Hall element shape. The experimental Hall element is bridge-shaped as shown in Fig. 2. Subsequently, Corning 7059 glass is sputtered onto the substrate surface in order to avoid migration of impurities from the ferrite substrate to the InSb film later formed.

As schematically shown in Fig. 1, an approximately 8-μm thick InSb film is deposited on the substrate surface. After stoichiometric InSb deposition, microzone melting is carried out; the substrate is passed under an electrically-heated nichrome wire as shown in Fig. 3. The molten zone is kept 1 mm wide by controlling the heating current. The crystallite sizes thus formed are about 0.5 mm × 3.0 mm. The details of the InSb deposition and the melting process are as described in a previous paper [14].

After microzone melting, the InSb film is lapped on a tin plate using submicron-diameter diamond powder until the 7059 glass surface appears. At this stage, InSb films of the Hall element shape are left in the grooves formed beforehand, resulting in a planar substrate surface, as shown in Fig. 1. The film thickness d is regulated by the sputtered SiO₂ layer to within ±0.05 μm error. By careful lapping, the thickness dependence of mobility μ_H of InSb films can be estimated. The measured values are higher than the ones obtained before by Wieder [19], [20] and Teede [21] for the thickness range...
of 0.4-2.0 μm [14], [22]. The obtained mobilities of above 6 m²/V·s at thicknesses above 1.4 μm suggest that our films include ionized impurities on the order of 1 X 10²² m⁻³, as will be seen in the next section. The Hall coefficient RH measured at 25 ± 3°C are fairly independent of film thickness and in the range of 340-380 cm³/C [22].

After the mechanical lapping, InSb films are thinned by no more than 0.3 μm with a conventional Ar-ion sputtering or a chemical etching to remove the anticipated surface damage. Subsequently, a simultaneous annealing and doping treatment is carried out; the InSb films are heated to 350°C in vacuum or inert gas atmosphere after covering the substrate surface with a powder dopant including a I, II, IV, or V element. This results in an increase in the Hall coefficient RH of a 1.4-μm thick film from 367 to 509 cm³/C and a decrease in the mobility μH from 6.12 to 4.83 m²/V·s, for a typical example. This indicates that the ionized-acceptor concentration is increased by 2-3 X 10²² m⁻³, according to the theoretical calculation in the next section. A detailed analysis of this process is given elsewhere [15].

Besides the doping effect, the above heat treatment reduces the current noise generated between Hall electrodes under dc bias current. The observed noise voltage (rms value) N is the vector sum of Johnson noise N0 and current noise of 1/f-type spectrum NC as given by

\[ N = (N_0^2 + N_C^2)^{1/2}. \] (1)

The current noise (rms value) N_C is governed [15] by the formula,

\[ N_C = K \rho(T) (R_H(T))^{1/2} J \] (2)

where K is the noise intensity coefficient, ρ is the resistivity, and J is the bias current density. The value of K is independent of J and of element temperature T. The annealing decreases K by a factor of 3, e.g., from 1.2 X 10⁻⁸ to 3.6 X 10⁻⁹ C/m²/μm². Therefore, it is conjectured that the heat treatment reduces some kinds of crystal defects or electron traps, although it may generate thermal acceptors in the films [23].

After the simultaneous annealing and doping treatment, a passivation glass layer is formed on the substrate surface to ensure element reliability, as illustrated in Fig. 1. Using conventional vacuum deposition and photo-etching techniques, Al electrodes are formed on top of the substrate surface. The electrical contacts are sufficiently ohmic at room temperature.

III. ELECTRICAL TRANSPORT PROPERTIES IN InSb NEAR ROOM TEMPERATURE (THEORY)

As described in the previous section, our InSb films with 1.4-1.7 μm thickness give a room-temperature mobility of approximately 6 m²/V·s. This value is comparable to that of bulk single crystal; we assume in this paper that surface diffuse scattering of conduction electrons does not play a dominant role in the films [19].

As a basis for calculation, the simple two-band model shown in Fig. 4 is used. The conduction band and the valence band are parabolic and the effective masses are assumed to be 0.014 m₀ and 0.43 m₀ respectively [24]. The band gap is assumed to be 0.18 eV at 300 K and 0.23 eV at 0 K, with temperature dependence assumed to be linear. The donor and the acceptor levels are assumed discrete and their activation energies are assumed to be zero.

On this basis, the Fermi level EF is calculated using Fermi-Dirac statistics for various donor concentrations N_D and acceptor concentrations N_A; the results are shown in Fig. 5. The electron concentration n and the hole concentration p are easily deduced from the well-known formulas,

\[ n(T) = D_c(T) \exp \left( \frac{E_F - E_c}{kT} \right) \] (3)

\[ p(T) = D_p(T) \exp \left( \frac{E_F - E_p}{kT} \right) \] (4)

where D_c and D_p are the effective density of states in each band, E_c and E_p are the bottom and the top energies of the respective band, and k is the Boltzmann constant. The temperature T used in Fig. 5 is 300 K (27°C). However, Fermi levels can be calculated for any temperature T and the temperature-dependent carrier concentrations n(T) and p(T) are easily deduced.

When electron (drift) mobility μ_n and hole (drift) mobility μ_p are known, the temperature-dependent Hall coefficient, RH(T), and the Hall mobility, μ_H(T), are given by

\[ R_H(T) = \frac{-(\gamma/e)(n(T)\mu_n - p(T)\mu_p)}{(n(T)\mu_n + p(T)\mu_p)^2} \] (5)

Fig. 3. Photograph of microzone melting apparatus; an 18 mm X 23 mm deposited InSb substrate is moving with its holder under an electrically heated 0.3-mm diameter nichrome wire.

Fig. 4. Two-band model for theoretical calculation; vertical axis is the energy and horizontal axis is the wave number. Both conduction band (the upper trace) and valence band (the lower trace) are parabolic. The heavy and light hole bands are not discriminated.
Fig. 5. Calculated Fermi level at 300 K as functions of acceptor concentration \(N_A\) and donor concentration \(N_D\). The \(N_D\) values are inserted in the figure (e.g., \(1 \times 10^{22}\) m\(^{-3}\)). The energy origin is set at the middle of the gap between conduction and valence bands.

\[
\mu_T(T) = eR_H(T)(n(T)\mu_n + p(T)\mu_p)
\]

where \(e\) is the charge of an electron and \(\gamma\) is the scattering factor. Here, \(\gamma\) is simply assumed to be \(3\pi/8\) for both electrons and holes [16]. Although the temperature dependences of \(\mu_n\) and \(\mu_p\) in a bulk single crystal may be obtained experimentally, we assume here that \(\mu_n\) and \(\mu_p\) for InSb thin films near room temperature are independent of temperature \(T\); the validity of this assumption will be examined experimentally in the next section.

The mobilities \(\mu_n\) and \(\mu_p\) are empirically known as functions of donor concentration \(N_D\) and acceptor concentration \(N_A\) at room temperature [16]. It is assumed here that the donors and the acceptors are fully ionized and behave the same as Coulombic scattering centers. Then the total ionized-impurity concentration \(N_I\) is given by

\[
N_I = N_D + N_A, \text{ (unit: m}^{-3}\).
\]

Under the assumption, we can approximate \(\mu_n\) and \(\mu_p\) as simple analytic functions of \(N_I\) according to [16] as follows:

\[
\mu_n = 7.6/\gamma M_n, \text{ (unit: m}^2/\text{V} \cdot \text{s})
\]

\[
\mu_p = 0.075/\gamma M_p, \text{ (unit: m}^2/\text{V} \cdot \text{s}),
\]

\[
M_n = 1 + 0.151(\log_{10} N_I - 21.000)^2 \text{ or } 1
\]

\[
M_p = 1 + \exp(1.427(\log_{10} N_I - 23.778)) \text{ or } 1
\]

where \(M_n\) and \(M_p\) are equal to 1 when \(N_I\) is small and the bracketed term in (10) or (11) is negative.

Based on the above model, experimentally observable quantities, \(R_H(T)\) and \(\mu_H(T)\), can be calculated as functions of \(N_A\) and \(N_D\). The results calculated for \(T = 300\) K are shown in Figs. 6 and 7. In the \((N_A, N_D)\) space shown in Fig. 6, Hall mobility \(\mu_H\) (contours shown by dotted lines) decreases with increases of \(N_I\), while Hall coefficient \(R_H\) (solid lines) assumes a maximum at around \(N_A = 6 \times 10^{22}\) m\(^{-3}\) and \(N_D < 2 \times 10^{21}\) m\(^{-3}\). Acceptor impurity concentrations above \(1 \times 10^{23}\) m\(^{-3}\) decrease the \(R_H\) value because of hole accumulation. On the other hand, the realized values in the \((\mu_H, R_H)\) space are bounded by a deformed triangular area, as shown in Fig. 7, which is characteristic of InSb crystals. Both Figs. 6 and 7 are convenient for deducing \(N_A\) and \(N_D\) from the measured values of \(\mu_H\) and \(R_H\). The comparable experimental data on \(\mu_H\) and \(R_H\) in InSb thin films was given in a previous paper [12].

IV. DEVICE CHARACTERISTICS AND THE COMPUTER SIMULATION

Two representative specimens are chosen for computer simulation of device characteristics as functions of bias current. One (J375-C2) is a Hall element treated only by the microzone melting followed by mechanical lapping. The other
(1A-3) is a high-performance Hall element treated the same as the first, but with the additional simultaneous annealing and doping. The element shape is fixed as shown in Fig. 2 because element noise strongly depends on shape.

A. Characterization of the Device

1) Transport properties of each film are examined experimentally as shown in Fig. 8. Mobilities $\mu_H$ are fairly insensitive to the bias current $I$ for both specimens. This is compatible with the assumption that $\mu_H$ is independent of temperature $T$. On the other hand, Hall coefficients $R_H$ decrease considerably with increase of $I$. This tendency is due to Joule heating of the elements, as will be shown later on. The acceptor and the donor concentrations, $N_A$ and $N_D$, for both specimens are estimated from the measured $\mu_H$ and $R_H$ using Figs. 6 and 7, and are summarized in Table I.

2) As seen in Fig. 9, the observed current noise $N_C$ depends linearly on $I$ in the low current range of $I < 10$ mA, as expected from (2). The deviation from linearity at high currents is also due to Joule heating, as will be clarified later on. The corresponding $K$ values are estimated from this measurement and recorded in Table I.

The noises are observed using an amplifier with a flat frequency response and with a $10^2$-$10^4$ Hz passband.

3) As is well known, Hall voltage $S$ under a magnetic flux density $B$ is given by

$$S = R_H(T) BJ/d = wR_H(T) BJ$$

(12)

where $w$ is the element width, in this case 0.2 mm. The observed $S$ at $B = 1$ mT (10 G) saturates because of Joule heating at $I = 30$ mA as shown in Fig. 9.

The sensitivity of Hall elements is conventionally evaluated
by the product sensitivity \( K_H \), which is defined as

\[ K_H = S/B. \]

In the linear region of the graph of \( S \) against \( I \) curve, the \( K_H \) values for both specimens are as high as 30 and 40 mV/\( \text{mA} \cdot \text{kG} \), as summarized in Table I. In this estimation, the effect of attached magneto-permeable materials like ferrite on element temperature \( T \) is assumed here that the element heat transfer into the air and the substrate is proportional to the difference between element temperature \( T \) and the temperature of environmental air \( T_0 \). The balancing equation is written as

\[ (l/\rho d) J^2 = \alpha (T - T_0). \]

(15)

where \( I \) is the effective length of the specimen shown in Fig. 2 and \( \alpha \) is the heat transfer constant. Length \( I \) is put as 1.3 mm, which is equal to the distance between current-supplying electrodes. First, we put \( T = T_0 \) and calculate \( \mu_H \) and \( R_H \) from the given \( N_A \) and \( N_D \). Second, using (15), \( T = T_1 \) is calculated for a given current density \( J \) and \( \mu_H \) and \( R_H \) are recalculated. Repeating this procedure until \( T_1 \approx T_{i+1} \), the self-consistent temperature \( T \) is obtained as \( T_1 \) at a given current density \( J \). This calculation includes the effect of temperature dependences of Fermi-Dirac statistics, bandgap energy, and the carrier concentration formulas given by (3) and (4).

C. Comparison of the Theoretical Calculation with the Experiments

In order to calculate the device characteristics for specimens J375-C2 and 1A-3, we adopted the values listed in Table I for \( d, N_A, N_D, K, T_0, N_C \), and \( \alpha \). The calculated results are shown in Figs. 8 and 9 by solid lines and agreed quantitatively with the experiments. The heat transfer constant \( \alpha \) was chosen to give the best fit of the theoretically calculated values to the measured dependence of \( R_H \) on bias current \( I \). Using the value for \( \alpha \) chosen this way, the element temperature \( T \) for each specimen are deduced and plotted as solid lines in Fig. 8 as functions of \( I \).

The element temperature rise due to Joule heating plays the dominant role in determining the device characteristics; the saturation of \( S \) and \( N \) with the increase of \( I \) and the corresponding decrease of \( R_H \) are results of the element temperature rise.

V. APPLICATION TO AUDIO HALL HEADS

A. Magnetic Head Structure

The performance of Hall head was first examined by Camras [9], using Ge and InSb semiconductor Hall elements. However, the highest frequency that the heads could detect was 3 kHz. According to recent specifications for cassette tape deck, Hall heads able to reproduce high-frequency signals up to 20 kHz are required.

As is well known, Hall heads can only pick up the recorded signals on a tape; recording has to be done by a separate coil head.

To meet the above requirements, two-channel (stereo) recording coil heads are combined with two-channel (stereo) Hall heads into a single body, as shown in Fig. 10. Since the

| Table I
| Device Parameters for Two Representative Specimens |
| Parameter | Specimen J375-C2 | Specimen 1A-3 | Units |
| \( d \) | 1.6 | 1.35 | \( \mu \text{m} \) |
| \( \rho_{\text{H}} \) | 6.45 | 4.10 | \( \Omega \cdot \text{cm} \) |
| \( \rho_{\text{H}} \) | 451 | 559 | \( \Omega \cdot \text{cm} \) |
| \( k_{\text{H}} \) | 0.0042 | 4.84 \( \times 10^{-9} \) | \( \Omega \cdot \text{cm} \) |
| \( y \) | 3.8 \( \times 10^{-9} \) | 8.9 \( \times 10^{-9} \) | \( \Omega \cdot \text{cm} \) |
| \( k \) | 6.2 \( \times 10^{-9} \) | 2.1 \( \times 10^{-9} \) | \( \Omega \cdot \text{cm} \) |
| \( T_0 \) | 27 \( \times 10^{-3} \) | 27 \( \times 10^{-3} \) | \( \Omega \cdot \text{cm} \) |
| \( \beta \) | 3.45 | 5.66 | \( \Omega \cdot \text{cm} \) |
| \( n \) | 0.52 | 0.53 | \( \Omega \cdot \text{cm} \) |
| \( v_0 \) | 0.40 | 0.46 | \( \Omega \cdot \text{cm} \) |
| \( S/N \) | 76.5 | 78.6 | \( \Omega \cdot \text{cm} \) |
| \( S/N \) | 79.7 | 82.3 | \( \Omega \cdot \text{cm} \) |
| \( K_H \) | 30 | 40 | \( \Omega \cdot \text{cm} \) |
| \( \alpha \) | 4.8 \( \times 10^{-3} \) | 7.4 \( \times 10^{-3} \) | \( \Omega \cdot \text{cm} \) |

*Measured at 14 \( \times 10^6 \) \( \Omega \cdot \text{cm} \).
**Measured at 14 \( \times 10^6 \) \( \Omega \cdot \text{cm} \) and 1 \( \Omega \) \( \mu \text{m} \).
***Measured at 14 \( \times 10^6 \) \( \Omega \cdot \text{cm} \) and 1 \( \Omega \) \( \mu \text{m} \).
Hall elements are approximately one tenth the volume of conventional playback coils, they are easily combined with the recording heads. In addition, to raise the upper frequency limit, we adopted the following rear-gap type Hall head structure [9]. Hall element itself can respond to a high-frequency signal up to giga-Hertz range in principle.

The tape magnetic flux is collected by a front tip consisting of two ferrite core pieces bonded by glass 1 µm thick, as illustrated in Fig. 11. The gap makes it possible to detect 17-20 kHz cassette tape signals [17]. A Hall element is sandwiched between the other pair of ferrite core pieces (the rear tip). Each core piece of the rear tip is fastened to one of the front tip core pieces, forming a magnetic circuit through which tape magnetic flux can easily pass. To fabricate the rear tip, a Hall element formed on one Ni-Zn ferrite substrate (the A-piece) and the other Ni-Zn ferrite core piece (the B-piece) are glued with a resin. The B-piece is shaped so as to concentrate the magnetic flux on the Hall element and to strengthen the magnetic flux density; its cross-sectional area decreases as the contact with the Hall element surface is approached [18].

For practical applications, a more simple Hall element with only four electrodes, a pair of Hall electrodes and a pair of current-supplying electrodes, is used instead of the eight-electrode shape shown in Fig. 2. The Hall element shape used is shown in Fig. 12 and in the photograph in Fig. 10.

B. Element Thickness Design and the SNR

In rear-gap type Hall heads, the thinner the Hall element, the higher the Hall head sensitivity. This is because more magnetic flux can pass through the rear tip and the Hall element. However, the thinner the element, the higher the element noise becomes because of the major increase of the noise intensity coefficient $K$. Experimentally, $K$ is found to be approximately proportional to the inverse of the film thickness, $d$ [25]. Therefore, $d$ should be determined so as to maximize the Hall head SNR with reference to the thickness dependence of the element SNR. The element SNR measured in a 1-mT (10-G) flux density and at $J = 4 \times 10^7$ A/m² is shown in Fig. 13.

Considering recent developments in playback head design, the Hall element SNR should be high enough to obtain a head SNR of more than 55 dB, which is the SNR of conventional coil playback heads. To meet this requirement, the element SNR should be at least 78 dB. Therefore, in reference to Fig. 13, the semiconductor film thickness $d$ should be $1.4 \pm 0.05$
The total Hall element thickness forming the rear-tip gap is 2.0 \mu m because of the 0.3 \mu m thick glass passivation and undercoating layers. The details of the thickness determination are discussed elsewhere [18].

For practical applications, the bias current \( I \) for Hall heads should be chosen with reference to the temperature rise of the head surfaces caused by the element temperature rise given in Fig. 8; \( I = 30-40 \) mA is appropriate for cassette-type combination Hall heads shown in Fig. 10.

C. Head Signal Level

The head output level is now considered when the "normal" cassette tape is played. The "normal" tape has the following frequency-dependent magnetic flux:

\[
\phi(f) = \phi_0 (1 + (2\pi f \tau_1)^2)^{1/2}/(1 + (2\pi f \tau_2)^2)^{1/2} \tag{16}
\]

where \( f \) is the signal frequency, \( \phi_0 \) is the standard recorded flux level, and \( \tau_1 = 3180 \) \mu s and \( \tau_2 = 120 \) \mu s, the standard cassette tape time constants. The magnetic flux brought into the head front tip is given by \( \phi(f) \Gamma(f) \), where \( \Gamma(f) \) is the efficiency of the gap structure [17]. This efficiency is approximately equal to unity for low-frequency signals. Since the head magnetic circuit has a flux leakage in various ways, some part of the above flux, at a rate of \( \xi \), passes through the Hall element in the rear gap. The rate \( \xi \) slightly depends on the area of B-piece at the contact and is simply determined by an equivalent magnetic-circuit consideration. Thus the magnetic flux density applied to the Hall element becomes

\[
B(f) = \xi (a, b) \phi(f) \Gamma(f) ab \tag{17}
\]

where \( ab \) is the area of the B-piece at the contact, \( a \) is the length, and \( b \) is the width. The length is parallel to the Hall element current. The smaller the contact area \( ab \), the higher the \( B(f) \). Therefore, the contact area is made smaller than

\[
\mu m. \quad \text{For this } d, \text{ the element SNR is } 78 \text{ dB at } J = 4 \times 10^7 \text{ A/m}^2 \text{ and } 81-82 \text{ dB at } I = 40 \text{ mA as listed in Table I. The SNR values shown in Fig. 13 can be increased by approximately } 3 \text{ dB by increasing the element bias current, as seen in Fig. 9.}

In this case, the total Hall element thickness forming the rear-tip gap is 2.0 \mu m because of the 0.3 \mu m thick glass passivation and undercoating layers. The details of the thickness determination are discussed elsewhere [18].

For practical applications, the bias current \( I \) for Hall heads should be chosen with reference to the temperature rise of the head surfaces caused by the element temperature rise given in Fig. 8; \( I = 30-40 \) mA is appropriate for cassette-type combination Hall heads shown in Fig. 10.

D. Head Noise Level

The Hall head noise level is given directly by the element noise level in (1). The frequency-dependent terms in (1) and (2), \( N_0 \) and \( K \), are important in order to correlate the element SNR and the Hall head SNR later on.

The Johnson noise \( N_0 \) is experimentally defined as the noise voltage observed when \( J = 0 \). This noise is composed of two parts; that coming from equivalent input noise-resistance \( r \) of the preamplifier and that coming from output resistance \( r_0 \) of the Hall element. The \( r_0 \) is empirically given by \( 3.9 \times 10^6 \rho \) \Omega and ranging 500 to 200 \Omega depending on bias current density \( J \), where \( \rho = R_H/\mu_H \) is expressed in unit of \( \Omega m \). When the temperature of the amplifier or the environment air is \( T_0 \) and the element temperature is \( T, N_0 \) is given by the following expression:

\[
N_0^2 = 4k(T_0 r + T_0(T)) \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} df \tag{19}
\]

where the amplifier passband is set from \( f_1 \) to \( f_2 \).

According to a previous paper [15], the noise intensity coefficient \( K \) of 1/f noise can be expressed as

\[
K^2 = \frac{X e}{f_2 - f_1} \int_{f_1}^{f_2} df \frac{1}{f} \tag{20}
\]

where \( X \) is a process-dependent parameter.
The effect of a noise reduction system like Dolby system is connected to the output electrodes or Hall electrodes. The Hall head SNR will increase much more than that of conventional coil heads. Such a change of tape flux function $\phi(f)$ will be possible when new magnetic recording materials for tapes are developed. The advent of metal tapes is, therefore, favorably expected for widespread Hall head applications.

**F. Advantages of Hall Head**

The advantages of Hall heads over conventional coil playback heads come from the difference of the principles: Hall heads detect magnetic flux directly as seen in (18), while coil heads detect the time-derivative of the flux. As a result, Hall head outputs are independent of signal frequency and tape speed; these characteristics are more effective without the equalization. Moreover, Hall head output can be increased by the dc bias current according to the Hall effect principle.

The audio-use Hall heads have the following advantages.

1) Transient responses for pulse-like input signals are superior to those of conventional coil heads because the head output impedance is purely resistive and not inductive. Since in principle the head output waveform is not distorted, phase distortion in all frequency ranges is comparatively small.

2) The head output voltage $V^*$ in the "normal" cassette tape playback is approximately 3 mV for most audio frequency ranges. This value is higher than that of the coil head, e.g., by factors of 10 and 3 at 333 Hz and 1 kHz, respectively. Thus the head SNR is superior to that of the coil head by more than 10 dB, especially in the low frequency range.

3) The head SNR $S_h/N_h$ in the overall audio frequency range $(f_1 = 20 \text{ Hz}, f_2 = 20 \text{ kHz})$ is superior to that of the coil head by some 2-4 dB on the average. The maximum value ever obtained is 60 dB in the "normal" tape playback.

The above advantages result in a high-fidelity reproduction of audio tape sounds. Details of Hall head characteristics are described elsewhere [17].

The other applications of Hall heads such as multichannel pickup of video signals and digital data are promising. Hall heads are also useful for detecting absolute values of tape magnetization with 1-μm resolution [26].

**VI. CONCLUSIONS**

A low-noise InSb thin film Hall element with an SNR of 82 dB under a 1-mT (10-G) magnetic flux density has been developed and applied to Hall heads for the cassette tape decks for the first time.

The fabrication processes and the device characteristics of InSb thin film Hall elements were described.

Transport properties of InSb at room temperature were first calculated semiempirically, especially in relation to the semiconductor purity. Using the results of these calculations and a 1/f noise formula [15], computer simulation of the Hall element characteristics was successfully accomplished. The theoretically calculated Hall voltage, noise voltage, and the element SNR agreed quantitatively with the experimental results. A rise in element temperature due to Joule heating is...
necessary to explain the device characteristics under dc bias current.

In order to use a Hall element in a tape deck head, the formula for the head SNR was defined for the first time and related to the Hall element SNR. The Hall head SNR compared favorably with that of conventional coil heads, and related to the Hall element SNR. The Hall head SNR advantages were also described.

ACKNOWLEDGMENT

The authors would like to express their appreciation to Prof. A. van der Ziel of University of Minnesota for his discussion of noise reduction mechanisms. The authors are also grateful to Dr. M. Camras of Illinois Institute of Technology for his discussion and comparison to his Hall head experiments. The authors are grateful to Dr. H. Watanabe, Dr. S. Taniguchi, Dr. G. Kamoshita, and Dr. T. Miura for their invaluable discussions during Hall head and element developments. The authors are also grateful for support from M. Murai, T. Kubota, D. Oshima, T. Ketori, J. Morikawa, T. Ketori, and H. Hanawa throughout this work. The authors would like to thank Dr. E. Yamada for his discussions and Application and Development of InSb thin film Hall elements, published.

REFERENCES