Paper

FeCoBN Magnetic Thin Film Inductor for MHz Switching Micro DC-DC Converters

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In order to obtain higher efficiency of the micro switching dc-dc converter using thin film magnetic device, FeCoBN magnetic film for thin film inductor was newly developed, which had high saturation magnetization of about 1.7 T, and high electrical resistivity over 3 $\mu\Omega\cdot$m. Consequently, a newly fabricated magnetic thin film inductor using the FeCoBN magnetic film had lower power loss due to the small eddy current loss. 5 MHz switching buck and boost converters using the new thin film inductor had higher efficiencies than those of the conventional micro switching dc-dc converters.

Key words: Thin film inductor, FeCoBN magnetic thin film, Micro dc-dc converter

I. Introduction

Recently, a great interest has been attracted in the planar magnetic devices such as thin film inductor and thin film transformer for low power dc-dc converters [1] – [5]. The magnetic thin film devices operating at high frequencies have many advantages over the conventional bulk magnetic devices ; better thermal management and higher power density. The very small size converters using the magnetic thin film devices will be used for the various handy electronic systems such as cellular phone, note book type computer, and other digital systems. The secondary batteries, Ni-MH battery, Li-ion battery and others, are utilized for the energy sources in the handy digital systems. Therefore, for a long time operation of the handy digital system, the converter efficiency should be as high as possible, and the power loss of the magnetic thin film device should be as small as possible.

The authors reported the magnetic thin film inductors for 5 MHz switching boost dc-dc converter [1][2]. The developed magnetic thin film inductors consisted of an inner planar spiral coil between the top and bottom soft magnetic films. Some researchers also reported the thin film magnetic devices and applications to dc-dc converters. Mino et al.[3] fabricated a micro transformer consisting of the two copper solenoid windings made by photo-lithography technique, and of the amorphous soft magnetic film. Lotfi et al. [4] reported a micro transformer using the electroplated permalloy (Ni-Fe) film, and they applied it to a gate drive transformer for power MOS- FET in the power electronics circuits.

In these researches on the thin film magnetic devices, the magnetic film materials for devices : CoZrNb, FeCo BC, CoZrRe and Ni-Fe, had the excellent soft magnetic properties ; low coercive forces, high permeabilities. However, their electrical resistivities were not so high.

In the thin film magnetic devices with an outer magnetic core structure, the perpendicular leakage magnetic flux passing through the magnetic layer gives rise to large in-plane eddy current [2]. In order to suppress the in-plane eddy current, it is very important to increase the electrical resistivity of the magnetic material. In addition, the rated current of the inductor strongly depends on the magnetic saturation of the magnetic film used, hence the magnetic film material should have saturation magnetization as high as possible.

This paper describes a newly developed magnetic thin film inductor for MHz switching dc-dc converters. For getting small power loss and large rated current of the thin film inductor, the FeCoBN soft magnetic thin film was newly developed. In the next sections, some properties of the magnetic film material, the development of the FeCoBN magnetic thin film inductor and its application to 5 MHz switching dc-dc converters are reported.

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Table 1 Specifications of FeCoBN magnetic film.

Deposition method	DC magnetron sputtering
Sputtering target	Sintered target
Film composition	$Fe_{59}Co_{20}B_{14}N_7$
Microstructure	Nanocrystalline
Saturation Magnetization	1.7 T
Coercive force	20 A/m
Anisotropy field	1440 A/m
Magnetostriction	unknown
Electrical resistivity	≧ 3 μΩ・m
Etching method	
(1) Etching mask	OFPR-800 Photo-resist
(2) Etchant	60 ℃ -Acid solution mixture
(3) Etchant composition	H_3PO_4 : CH_3COOH : HNO_3 : H_2O = 71.5 : 10.2 : 1.9 : 16.4 (vol.%)

Annealing condition ; 586 K, 180 min., 500 Oe, in vacuum.

II . Fe-Co-B-N Magnetic Thin Film

A. Fabrication method

The FeCoBN magnetic thin film [6] was fabricated by dc magnetron sputtering using a sintered target. The specifications and after annealing condition of the film are shown in Table 1. The FeCoBN film had amorphous structure as deposited state, and then after dc magnetic field annealing, the microstructure was transformed to nanocrystalline structure consisting of the Fe-Co rich crystal grains surrounded by BN rich matrix. Consequently, the electrical resistivity of the FeCoBN film was two times higher than the conventional magnetic films (CoZrNb, FeCoBC, CoZrRe, ……), which was due to the high resistivity BN rich matrix.

B. Static magnetic property

Uniaxial magnetic anisotropy was induced by after dc magnetic field annealing. Fig.1 shows a static magnetization curve measured in the hard magnetization direction. Coercive force H_{ch} was about 20 A/m (0.25 Oe), and saturation magnetization I_s was about 1.7 T (17 kG). I_s value was higher than those of the conventional magnetic films used in the thin film inductors. Anisotropy magnetic field H_k was estimated to be about 1440 A/m (18 Oe), hence static relative permeability in the hard magnetization direction was about 940.

C. Frequency dependence of permeability

The permeability in the hard magnetization direction was measured by using thin film permeance meter [7]. Fig.2 represents a frequency dependence of the complex permeability μ_s of 1 μm thick FeCoBN magnetic film;

$$\mu_s = \mu_s' - j\mu_s'' \qquad (1)$$

where μ_s' and μ_s'' are the real and imaginary parts of relative complex permeability, μ_s'' means a magnetic loss component. From the measured results, μ_s' was constant up to 300 MHz, and the value was about 900. A loss factor tan δ defined as μ_s''/μ_s' was about 0.1

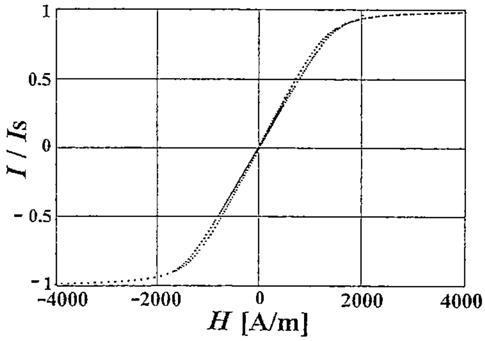


Fig.1 Static magnetization curve of the FeCoBN magnetic film measured in the hard magnetization direction.

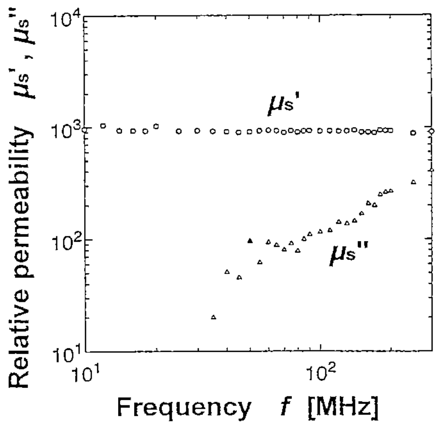


Fig.2 Frequency dependence of the relative complex permeability of the 1 μm thick FeCoBN magnetic film.

at around 100 MHz. The loss factor was lower than the conventional amorphous soft magnetic films, which was due to the eddy current suppression by higher electrical resistivity of the FeCoBN film.

D. Wet etching method

To fabricate the magnetic thin film devices, the magnetic film should be etched by easy method such as wet-etching process. The FeCoBN magnetic film was easily dissolved in the phosphorus acid. However, since the viscosity of the phosphorus acid was relatively high, the uniformity of the wet-etching was not so good. An acid solution mixture for FeCoBN film wet-etching was introduced here. The composition of the acid solution mixture is shown in Table 1. The acid solution mixture was ordinarily used for the aluminum wet-etching in the semiconductor device process. The acetic acid and nitric acid played an important role in the viscosity reduction in the solution mixture. This wet-etching was the same as the method for FeCoBC film [8]. As described later, FeCoBN/AlNx multilayered magnetic core was used in the newly developed thin film inductor. Since the AlNx interlayer film was also dissolved in the same acid solution mixture [8], the FeCoBN/AlNx multilayered film was wet-etched at one time.

Table 2 Specifications of the FeCoBN thin film inductor.

Inductor size	6310 μm × 3466 μm
Planar coil	Size : 6010 μm × 2766 μm Pattern : Double rectangular spiral Material : 50 μm-thick electroplated copper Line / spacing : 36 / 34 μm Division number for conductor line : 2 Number of coil turns : 3 × 2
Magnetic core	FeCoBN/AlNx multilayered film · FeCoBN layer : 1.5 μm × 4 layers · AlNx layer : 0.4 μm × 5 layers
Insulator	10 μm-thick polyimide layer

Ⅲ. FeCoBN Magnetic Thin Film Inductor

A. Device structure and fabrication procedure

<A.1> Device structure

An inductor structure is schematically illustrated in Fig.3. An inner electroplated copper planar coil, which had the double rectangular spiral pattern [2] and the number of planar coil turns of 6, was sandwiched by a top and a bottom magnetic core. The magnetic core was FeCoBN/AlNx multilayered film with uniaxial magnetic anisotropy. Its easy magnetization axis was the same direction of the longitudinal axis of the rectangular spiral coil, hence the magnetic field generated by ac coil current was applied to the hard magnetization direction. Consequently, the rotation magnetization process was dominant, which had an excellent frequency characteristic as shown in Fig.2. The upper and lower insulating layers between planar coil and magnetic cores were the spun on polyimide films. The thin film inductor was fabricated on a 5inch-diameter Si-wafer with SiNx thin layer deposited on the top surface.

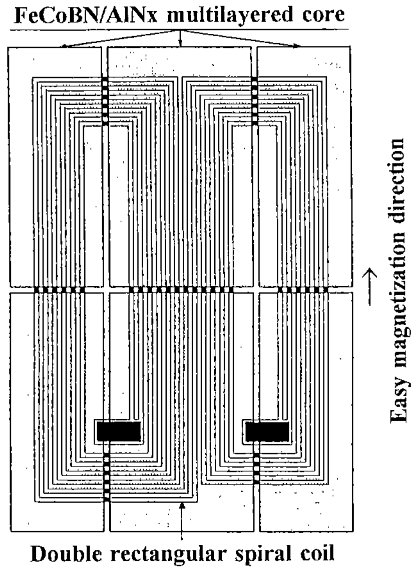
<A.2> Eddy current suppression techniques

To suppress the high frequency losses due to the eddy currents in the coil conductor and magnetic core, the eddy current suppression techniques were introduced.

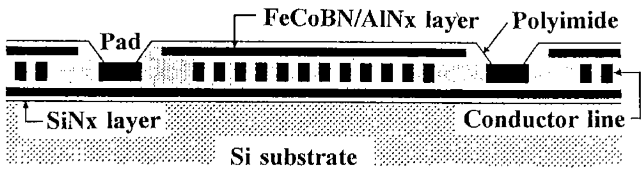
The perpendicular leakage magnetic flux passing through the conductor line and magnetic core gave rise to the in-plane eddy currents. If the perpendicular flux density B_g is passing through the conductor line with thickness t_c and line-width w, the equivalent resistance r_c per unit conductor line-length is shown as follows [2];

$$r_c = \rho \frac{1}{t_c w} + \frac{4\pi^2 f^2 t_c w^3 B_g^2}{12\rho} \quad (\Omega/\mathrm{m}) \qquad (2)$$

where ρ is the resistivity of the conductor material, f is the frequency, and B_g has the r.m.s value, respectively. In Eq. (2), first term is the dc resistance per unit line-length, and second term means the equivalent eddy current resistance per unit line-length. It is very clear that the eddy current resistance strongly depends on the line-width w. To reduce the equivalent eddy current resistance of the conductor line, the division structure for



(a) Top view



(b) Cross-section

Fig.3 Schematic illustration of the FeCoBN thin film inductor.

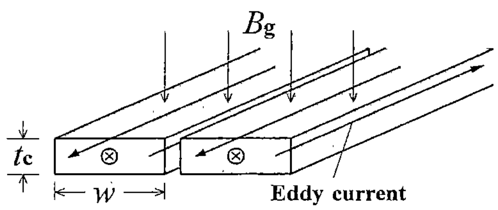


Fig.4 Division structure for the conductor line.

the conductor line, as shown in Fig.4, was introduced. Therefore, high frequency coil resistance was reduced effectively without increasing dc coil resistance. The authors already clarified that the division conductor line structure was very useful method for getting higher Q factor in the some experiments for the conventional FeCoBC magnetic thin film inductor [2].

The in-plane eddy current loss due to the perpendicular flux was also generated in the top and bottom magnetic cores. In the newly developed inductor, since the high resistivity magnetic film was used, the in-plane eddy current became small. To more suppress the in-plane eddy current in the magnetic layer, some slits were introduced to the magnetic core, as shown in Fig.3. Since the slits enabled to shorten the in-plane eddy current path, the in-plane eddy current loss was suppressed effectively. This method was also used in the conventional FeCoBC film inductor [2]. In addition the

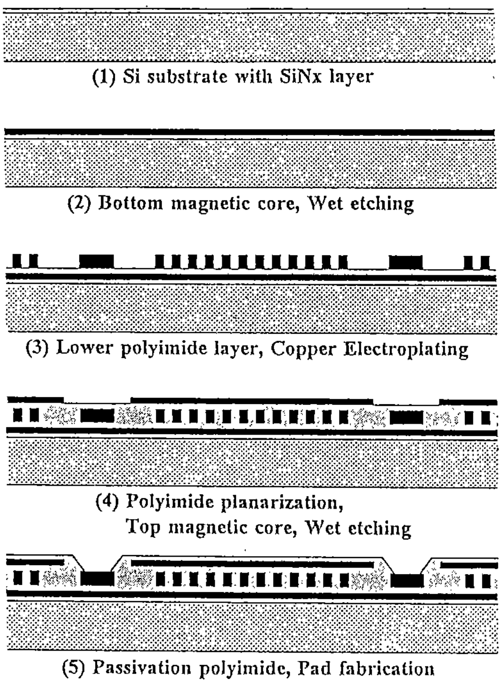


Fig.5 Fabrication procedure of the FeCoBN thin film inductor.

eddy current due to the in-plane magnetic flux passing through the magnetic core was suppressed by introducing the FeCoBN/AlNx multilayered structure.

<A.3> Fabrication procedure

Fig.5 shows the fabrication procedure of the thin film inductor. Although not shown in Fig.5, to induce the uniaxial magnetic anisotropy, dc magnetic field annealing was finally executed.

B. Small signal characteristic

Small signal frequency characteristic of the FeCoBN magnetic thin film inductor was measured by using an impedance meter (HP4194A). The experimental result is shown in Fig.6. For a comparison, an experimental result of the conventional FeCoBC magnetic thin film inductor [2] is also shown in the same figure. The new thin film inductor had higher quality factor Q than the conventional one. The maximum quality factor $Q_{max.}$ was about 15 at 7 MHz, and $Q_{max.}$ was higher than any conventional outer core type thin film inductor.

C. Large signal characteristic

Large signal characteristic of the thin film inductor was estimated by direct measurements of the voltage, current and power of the inductor. These measurements were based on the high frequency power amplifier (NF; 4055) and an oscilloscope (TEKTRONIX ;11403A). For a comparison, the conventional FeCoBC magnetic thin film inductor was also measured. Fig.7 shows the inductance L and quality factor Q versus coil current I curves measured at 5 MHz, where I is shown as the r.m.s value. Inductance L increased and quality factor Q decreased with increasing I in the small current region, but both values became nearly constant in the large coil current region. It is considered that the phenomena may be due to the magnetic hysteresis of the magnetic film. When the amplitude of the magnetic field H_a applied to the magnetic film is smaller than the coercive force H_c, the magnetic hysteresis phenomenon can be represented by Rayleigh magnetic loop [9]. In the the Rayleigh loop, the relative permeability μ_r and loss factor $\tan\delta_h$ are written as follows [9];

$$\mu_r = \mu_i + (\eta_r / \mu_o) H_a \quad (3),$$

$$\tan\delta_h = k H_a \quad (4),$$

where μ_i is the initial relative permeability, μ_o is the permeability in vacuum, η_r is the Rayleigh constant, and k is the constant, respectively. In Fig.7, the increase of the inductance in the small current region may be due to the increase of the permeability with increasing magnetic field in the Rayleigh region, and the reason for a degradation of the quality factor Q in the small coil current region is due to the increase of the loss factor with increasing magnetic field amplitude.

In Fig.7, the inductance and quality factor became constant over a critical coil current. The critical currents were 30 mA in FeCoBC thin film inductor, and 200 mA in FeCoBN thin film inductor, respectively. A difference between the critical coil currents of both thin

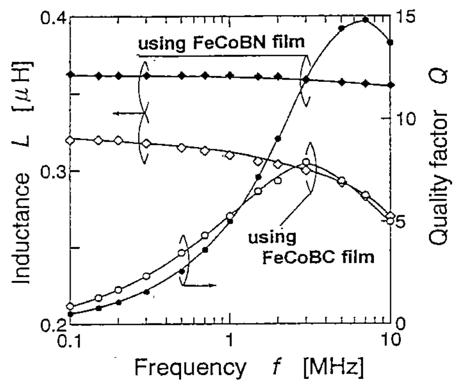


Fig.6 Small signal characteristic of the thin film inductor.

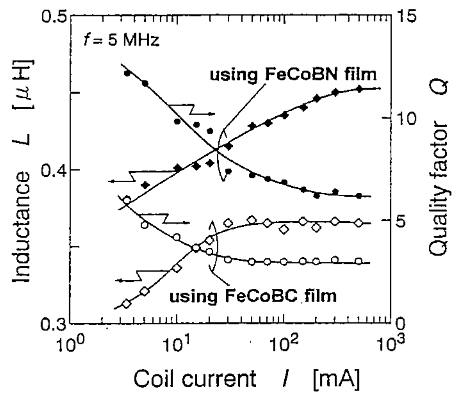


Fig.7 Large signal characteristic of the thin film inductor.

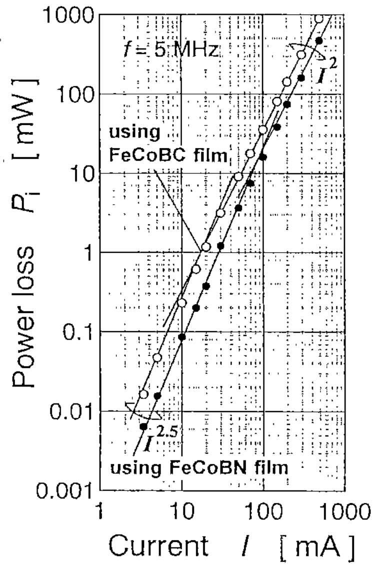


Fig.8 Relationship between dynamic power loss and coil current in the thin film inductor.

film inductors may be owing to the difference between the magnetic coercive forces of the FeCoBC and FeCoBN magnetic films. The coercive force of the FeCoBN magnetic film used in the thin film inductor degraded through the unstable device fabrication process ; thermal process such as annealing for magnetic film. However, even in the large coil current region, inductance and quality factor of the FeCoBN thin film inductor were higher than the conventional FeCoBC thin film inductor.

D. Power loss

Fig.8 represents the relationship between power loss P_i and coil current I. P_i was the dynamic power loss excluding the loss due to the dc coil resistance, hence P_i composed of the conductor eddy current loss and the magnetic loss. As shown in Fig.8, the large signal power loss of the newly developed thin film inductor was smaller than the conventional thin film inductor.

It was unknown here that either conductor eddy current loss or magnetic loss dominated the power loss P_i. However, the power loss P_i was proportional to $I^{2.5}$ in the small current region. As mentioned before, the Rayleigh hysteresis loss W_h is dominant in the low field H_a, which is represented as follows;

$$W_h = \frac{4}{3} \eta_r H_a{}^3 \qquad (5).$$

Since the field H_a is proportional to the coil current I, it is considered that the power loss in the small current region is close to the Rayleigh magnetic hysteresis loss.

Ⅳ. Application to DC-DC Converter

A. Experimental circuits

The developed thin film inductor was applied to the buck and boost dc-dc converters with a rated power of 1.5 W. Circuit configurations are shown in Fig.9. N-ch power MOS-FET (2SK2999) was used for a main switch, SBD (1FWJ43N) was used for a rectifier diode, C_1 and C_2 were the multilayer ceramic condensers with a capacitance of 0.5 μF, the new FeCoBN magnetic thin film inductor with 0.45 μH inductance was used as a L in Fig.9, respectively. For a comparison, the conventional FeCoBC thin film inductor with 0.37 μH inductance was also used.

In order to maintain an output dc voltage, an external rectangular waveform signal with an arbitrary duty cycle was applied to the MOS-gate. Switching frequency was 5 MHz. The buck converter was measured under the input voltage V_i of 5 V, and the output voltage V_o of 3 V. The boost converter was measured under the input voltage V_i of 3 V, and the output voltage V_o of 5 V.

B. Experimental results

Fig.10 and 11 show the converter efficiency versus output current curves in the buck and boost converters. Both converters using the FeCoBN thin film inductor had higher efficiencies than the converters using the Fe CoBC thin film inductor. Especially, the improvement of the efficiency was so much in the light load condition.

For a simple discussion, the power loss P_L of the thin film inductor operating in the dc-dc converter is approximately expressed as follows [1];

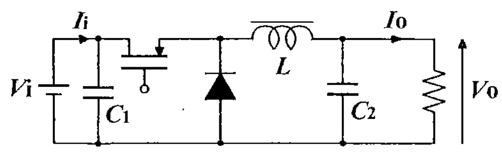
$$P_L = R_{dc} I_{dc}{}^2 + \frac{2\pi f L}{Q} I_p{}^2/3 \qquad (6),$$

where R_{dc} is the dc coil resistance, I_{dc} is the dc component of the coil current, I_p is the peak value of the ac triangular coil current, and

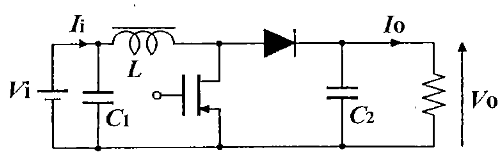
$$I_{dc} = I_o \quad \text{; buck converter} \qquad (7),$$

$$I_{dc} = I_i \quad \text{; boost converter} \qquad (8),$$

respectively. When the converters operate under the light load condition (I_o, I_i ; small), dc losses due to the dc coil resistance are very small. Therefore, to improve the light load efficiencies, ac loss of the inductor should be as small as possible. The FeCoBN thin film inductor had



(a) Buck converter



(b) Boost converter

Fig.9 Circuit configurations of the buck and boost dc-dc converters using thin film inductor.

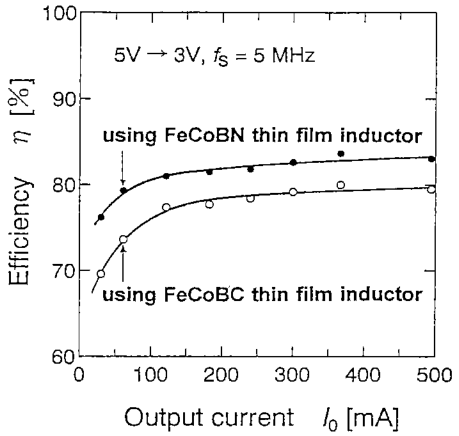


Fig.10 Relationship between converter efficiency and output current in the buck converter.

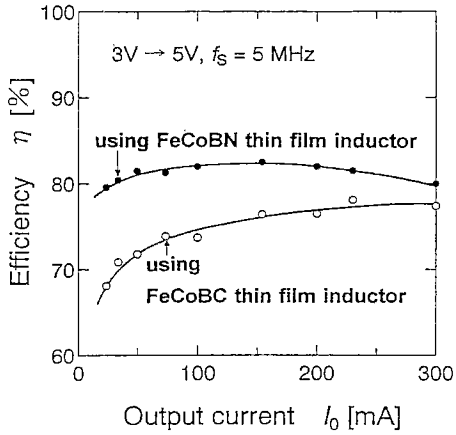


Fig.11 Relationship between converter efficiency and output current in the boost converter.

smaller ac loss than the conventional one, hence the light load efficiencies became higher.

V . Conclusion

FeCoBN magnetic film with high electrical resistivity and high saturation magnetization was newly developed, and it was applied to the outer magnetic core type thin film inductor. The newly developed thin film inductor had higher quality factor than the conventional thin film inductors, and enabled us to get the higher efficiencies of the micro switching buck and boost dc-dc converters.

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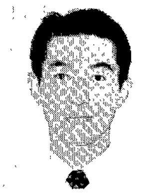

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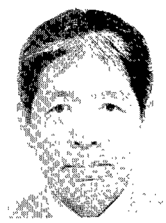

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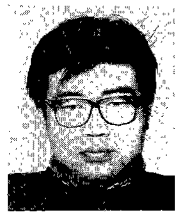

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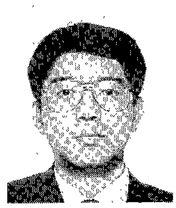

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