A Small-Signal Linear Equivalent Circuit of HEMT's Fabricated on GaAs-on-Si Wafers

Mitsuhiko Goto, Yasumitsu Ohta, Takashi Aigo, and Akihiro Moritani

***Abstract*—A new small-signal linear equivalent circuit for high electron mobility transistors (HEMT's) fabricated on GaAs-on-Si wafers, HEMT's-on-Si, has been proposed. The new equivalent circuit describes the microwave characteristics of HEMT's-on-Si much better than the conventional metal-semiconductor field-effect transistor (MESFET) equivalent circuit does. Influences of the pads, the GaAs-Si interface, and the Si substrate on the microwave characteristics are included in the circuit. It also has a great advantage in that it can separately analyze the intrinsic device characteristics and influences of Si substrate and GaAs-Si interface. Analyzes using the new equivalent circuit show that the crucial problem of HEMT's-on-Si is the larger values of the pad capacitances and the drain-source capacitances than those of HEMT's fabricated on GaAs bulk wafers, HEMT's-on-GaAs, and that the substrate resistivity is not an important factor for microwave performances of HEMT's-on-Si. The microwave performance was improved by the reduction of the pad capacitances.**

I. INTRODUCTION

GaAs-on-Si technology is promising to replace GaAs bulk IC's because it has some advantages such as high thermal conductivity, potential wafer-size expansion, and mechanical hardness of substrates. More than 50% higher thermal conductivity from devices on the top surface to the bottom surface of GaAs-on-Si wafers than using GaAs bulk has been reported [1]–[3]. This means a higher potential for GaAs-on-Si devices especially in power amplifier applications, in which GaAs devices have a great intrinsic advantage of high power-added efficiencies to Si devices. The potential wafer-size expansion and the mechanical hardness lead to higher yields, easier handling and lower cost productions. GaAs-on-Si also has advantages in that it contains a smaller amount of toxic elements, gallium and arsenic, and it is a solution to the problem of the limited material supply of gallium on earth.

Devices fabricated on GaAs-on-Si wafers such as heterojunction bipolar transistors (HBT's) [4] and field-effect transistors (FET's) [5]–[9] have been reported by many authors. High uniformity of threshold voltage of high electron mobility transistors (HEMT's) of one standard deviation less than 9 mV, which is better than HEMT's fabricated on GaAs bulk wafers, has been also reported [10]. This means large scale integrated circuits on GaAs-on-Si wafers are becoming more realistic applications. Not only discrete devices but also integrated circuits have been successfully fabricated on GaAs-on-Si wafers [11], [12].

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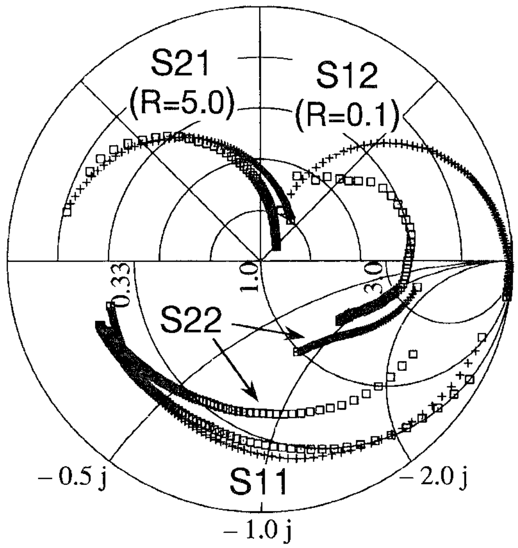


Fig. 1. Comparison of measured S-parameters of HEMT-on-Si and HEMT-on-GaAs.

Small-signal equivalent circuits of transistors are generally used for device characterization, device design optimization, and circuit design. A large-signal equivalent circuit is also proposed for the purpose of applications to the circuit design [13]. A metal-semiconductor field-effect transistor (MESFET) equivalent circuit model has been conventionally used for HEMT's [14], because the equivalent circuit of the intrinsic part of HEMT's is the same as that of MESFET's. However, the conventional MESFET equivalent circuit could not accurately describe the measured S-parameters of HEMT's fabricated on GaAs-on-Si wafers (HEMT's-on-Si) because they have different S-parameters' shapes from those of HEMT's fabricated on GaAs bulk (HEMT's-on-GaAs), as shown in Fig. 1.

The aim of this paper is to propose a new equivalent circuit which can accurately describe the characteristics of HEMT's-on-Si, and to clarify the essential factor that causes the difference in microwave characteristics between HEMT's-on-Si and HEMT's-on-GaAs. Sample preparations are mentioned briefly in Section II, measured microwave characteristics are shown in Section III, a new equivalent circuit is proposed in Section IV, analyzes using the equivalent circuit and an

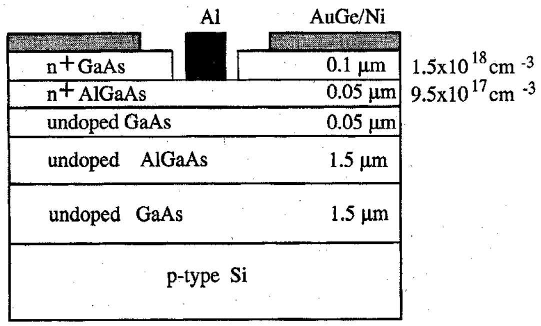


Fig. 2. Schematic cross section of AlGaAs/GaAs HEMT's-on-Si.

improvement are done in Section V, and the paper is concluded in Section VI.

II. Fabrication Process of HEMT-on-Si Samples [3], [9]

Fabricated HEMT's-on-Si are widely used AlGaAs/GaAs HEMT's. The HEMT structure used is illustrated in Fig. 2, which consists of a 1.5-μm–thick GaAs buffer layer, a 1.5-μm–thick AlGaAs buffer layer, a 0.05 μm (500 Å)-thick GaAs channel layer, a 0.05 μm (500 Å)-thick doped AlGaAs layer and a 0.1 μm (1000 Å)-thick doped GaAs cap layer (doping concentration is 1.5×10^{18} cm^{-3}). The carrier concentration of the doped AlGaAs layer was around 9.5×10^{17} cm^{-3}, which we have reported as the best for 500 Å-thick layer [9]. The aluminum mole fraction was about 0.25.

After the epitaxial growth by metal-organic chemical vapor deposition (MOCVD), HEMT's were fabricated. The devices have the gate length of 0.8 μm and the gate width of 210 μm. The source-drain spacing was 5 μm. The isolation of these devices was done by wet chemical mesa etching, and a silicon dioxide (SiO_2) dielectric layer was formed by chemical vapor deposition (CVD) to passivate the wafer surface. For the source and drain ohmic contacts, AuGe/Ni/Au layers were deposited and alloyed. After gate recess etching of the GaAs cap layer was done, an Al gate was then deposited. It should be noted that no special treatment was required to handle the 3-inch-diameter GaAs-on-Si in spite of the large warpage ($\approx$ 50 μm) of the wafer.

All pads were placed on the undoped AlGaAs buffer layer slightly etched during the mesa etching. The standard pad dimension was 50 μm $\times$ 50 μm.

III. Microwave Characterization

S-parameters were measured using the Cascade Microtech on-wafer probing system and the Hewlett Packard vector network analyzer 8510. The characteristic impedance is 50 Ω. The frequency range was 1 to 20 GHz. Substrates were grounded in order to avoid the fluctuation of bulk potential. Drains were biased to 2 V and gates were biased to the voltage at which the direct current transconductance has the best value.

Fig. 1 shows the comparison of the measured S-parameters of a HEMT-on-Si and a HEMT-on-GaAs, which were previously fabricated and measured, and are with pads of 80 μm $\times$ 80 μm. They were reported in [9].

TABLE I
Comparison of f_T's and f_{max}'s of HEMT's-on-Si with Different Pad Dimensions

Pad dimension (µm)	80	50
f_T (GHz)	6.4	11.7
f_{max} (GHz)	6.9	12.2

The most important difference between both HEMT's is observed in S_{22}. The magnitude of S_{22} of the HEMT-on-Si is larger than that of the HEMT-on-GaAs. The change in the phase with the frequency of S_{22} is also larger, which indicates a larger capacitance between the drain and source terminals. The larger capacitance of the HEMT's-on-Si suggests an influence of the doped thin layer with outdiffused Si at the GaAs-Si interface [15] and the conductive Si substrate. Although S_{11} of both HEMT's are almost on the same constant-resistance circle and its deviation is small, the phase of S11 of HEMT's-on-Si is shifted toward $-180°$ compared to that of the HEMT-on-GaAs. This indicates a larger capacitance between the gate and source terminals of the HEMT-on-Si. The difference in S_{12} indicates the difference in capacitances between the gate and source terminals, and between the gate and drain terminals. The smaller magnitude of S_{12} of the HEMT-on-Si is a good influence of using the Si substrate.

IV. New Equivalent Circuit

A. What is Required for the New Equivalent Circuit

As mentioned described above, the microwave performance of HEMT's-on-Si is affected by the Si substrate and/or the GaAs-Si interface. However, the conventional HEMT equivalent circuit, that is MESFET equivalent circuit, could not accurately describe the microwave characteristics of HEMT's-on-Si. We need to build another equivalent circuit for HEMT's-on-Si.

It was observed that current gain cut-off frequencies (f_T's) and maximum oscillation frequencies (f_{max}'s) calculated from measured S-parameters depend on the on the pad dimension as shown in Table I. F_T and f_{max} of the device with the smaller pads are larger than those of the device with the larger pads. This indicates that the microwave characteristics of HEMT's-on-Si are influenced by the pads. Our new equivalent circuit must include the influence of the pads.

We need to estimate the characteristics of the pads themselves. The best and ideal way is measuring $S-$parameters of pads without active devices, as described in [16] and [17]. Because all our test patterns have active devices, the mesas were etched off for the measurement. Pad characteristics were measured with another TEG device on the same wafer. S_{11} and S_{22} of pads are shown in Fig. 3. The area of the pads are 2500 μm^2 (50 μm $\times$ 50 μm). They are almost on the constant resistance circles and their deviations from the circles are small. This result indicates that the pads are expressed by series connections of resistors and capacitors. The capacitors represent capacitances between the pads and

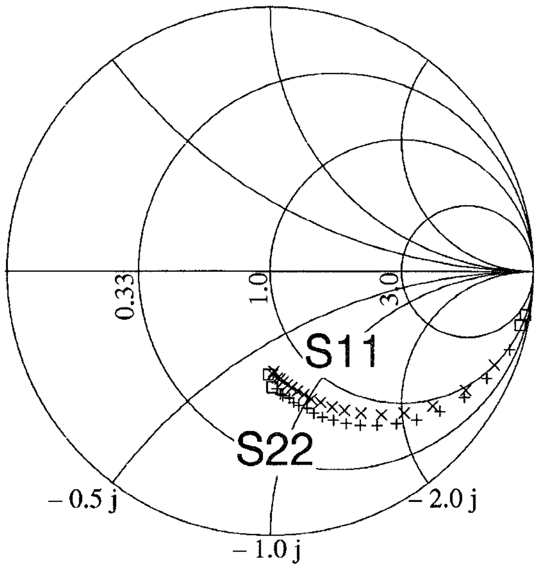


Fig. 3. Measured S-parameters, S_{11} and S_{22}, for pads of HEMT's-on-Si.

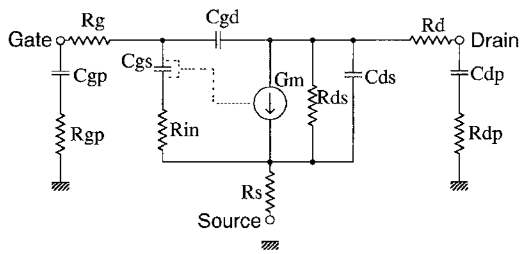


Fig. 4. New small-signal linear equivalent circuit of HEMT's-on-Si.

the Si substrate, and the resistors represent resistances due to the higher electrical conductivity of the Si substrate than GaAs bulk.

B. The Configuration of the New Circuit

Fig. 4 shows the new small-signal linear equivalent circuit. Four components, C_{gp}, R_{gp}, C_{dp} and R_{dp}, are added to the conventional MESFET equivalent circuit, for example, shown in [14]. C_{gp} and R_{gp} are added to the gate node, C_{dp} and R_{dp} are added to the drain node. The influence of the gate pads are expressed by C_{gp} and R_{gp}, and the influence of the drain pads are expressed by C_{dp} and R_{dp}. The capacitors C_{gp} and C_{dp} are generally used to express the capacitance of packages, for example, as in [18]. The discussion in the previous section indicates that pads on GaAs-on-Si wafers should be expressed by the series connections of resistors and capacitors. $C_{gs}, R_{in}, G_m, C_{gd}, R_{ds}$, and C_{ds} express the intrinsic part of HEMT-on-Si devices. They are also included in the conventional equivalent circuit.

Since HEMT's-on-Si use silicon as a substrate material, influences of 1) substrate capacitance, 2) electrical conductivity of the substrate, and 3) conductive layer at the GaAs-Si interface [15] should be taken into account in the new equivalent circuit. C_{gp} and C_{dp} mainly corresponds to capacitances between pads and the substrate. C_{ds} includes influences of capacitance due to the GaAs-Si interface and the Si substrate.

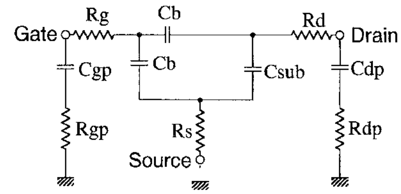


Fig. 5. Equivalent circuit of "cold" HEMT's-on-Si.

R_{gp} and R_{dp} are resistances due to the electrical conductivity of the Si substrate.

The characteristics of fabricated devices should be divided into the intrinsic device characteristics and influences of the Si substrate and of the GaAs-Si interface. Utilizing Si wafers as substrates influences only five components, $C_{gp}, R_{gp}, C_{ds}, C_{dp}$ and R_{dp}, in the new circuit. The other parameters represent the essential characteristics of HEMT's. The new circuit permits separate and easy analyzes of these two characteristics, which makes the indications for design and process optimizations clearer. This is a great advantage both to designs and fabrications of HEMT's and to GaAs-on-Si wafer characterizations and productions.

This circuit is also applicable to MESFET's-on-Si because the equivalent circuit of the intrinsic part of MESFET's is the same as that of HEMT's.

C. S-Parameter Fittings Using the Equivalent Circuits

Parameter fittings were done with the Hewlett Packard Microwave Design System (HP-MDS). The parameters are extracted by three steps to avoid accuracy degradation. The first step is the pad characteristics fitting, where C_{gp}, R_{gp}, C_{dp} and R_{dp} are fitted both for the normal bias condition and for the "cold" HEMT bias condition. The second step is the "cold" HEMT fitting, where R_g, R_s and R_d are fitted to the measured characteristics with the gate bias of -2 V and zero drain bias. The equivalent circuit used is shown in Fig. 5. Because the Si substrate is not depleted, C_{sub} is added to the "cold" FET circuit shown in [18]. It's the best that R_g, R_s and R_d are determined from dc measurements [18]–[20]. But, oscillations prevented us away from stable measurements. The third step is the intrinsic HEMT fitting, where $C_{gs}, R_{in}, G_m, C_{gd}, R_{ds}$ and C_{ds} are extracted.

The simulated S-parameters using the new equivalent circuit is shown in Fig. 6, with the comparisons with the measured values and with simulated characteristics using the conventional circuit. Solid lines show the simulated values using the new circuit, and pluses show the measured values. Both values are almost identical. The simulated values using the conventional circuit, shown by dotted lines, deviate much more from the measured values. The fitting error is defined as the RMS (root mean square) of relative errors of fitted S-parameters compared to the measured ones, as expressed by the following equation:

$$\text{Error} \equiv \sqrt{\frac{1}{4\cdot n}\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{n}\left|\frac{S_{ij}^{\text{fit}}(k)-S_{ij}^{\text{meas}}(k)}{S_{ij}^{\text{meas}}(k)}\right|^2} \quad (1)$$

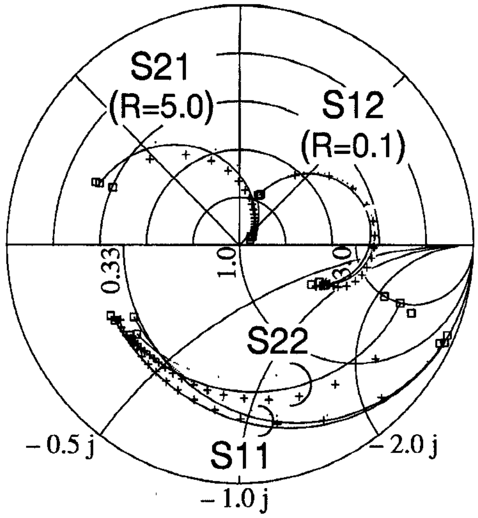


Fig. 6. Fitting result of S-parameters by the new circuit compared to the conventional circuit. Pluses (+): Measured data. Solid line: Fitted by the new circuit (error 6.0%). Dotted line: Fitted by the conventional MESFET circuit (error 13%).

where n is the data size, the number of frequencies at which S-parameters were fitted. The error using the new circuit was no greater than 6%, while the error using the conventional circuit was 13%. This indicates that the new circuit describes HEMT's-on-Si much better than the conventional circuit does.

V. Analyses Using the Equivalent Circuit

A. Extracted Parameters

Extracted parameters are listed in Table II. Magnitude of G_m shows a good agreement with the dc transconductance value measured with another TEG device, around 210 mS/mm, that is around 44 mS/210 μm. C_{gs} agrees with theoretically estimated gate-carrier capacitance, around 0.3 pF. This result indicates that the new equivalent circuit makes it possible to analyze the intrinsic capacitance and the pad influence separately. C_{ds} is a little larger than C_{sub}, the source-drain capacitance through the Si substrate. The difference is estimated to be the source-drain capacitance through the buffer layers. C_{gd} agrees with C_b, used for the "cold" HEMT (FET) equivalent circuit. This indicates that the gate-drain capacitance at the normal bias condition is the fringe capacitance. R_g shows an agreement with the estimated value, 12 Ω, from the resistivity and the dimension of the electrode. The resistance of the source electrode is estimated to be less than 0.02 Ω. R_s is considered to be mainly the resistance of the alloyed region. The resistance of the drain electrode is estimated to be 0.8 Ω. The difference, around 11 Ω, is considered to be the resistance of the alloyed region. The difference in the resistance of the alloyed region between R_s and R_d is due to the difference in the area of the region. The area of the alloyed region for the source is around ten times larger than that for the drain.

B. What Degrades the Microwave Performance of HEMT's-on-Si?

It is important to clarify whether capacitances or conductances degrade the microwave characteristics of HEMT's-on-Si. Their sensitivities are compared in Fig. 7(a). The sensitivity is defined as the normalized change in f_T or $f_{\max}$ divided by the normalized change in the concerned parameters. The sensitivity value of 1 means that if the parameter becomes, for example, twice the f_T or $f_{\max}$ becomes twice. The average sensitivity of the capacitances is about four times larger than that of the resistances. As to the resistances, while the sensitivity for f_T is larger than that of the capacitances, that for $f_{\max}$ is negative. This leads to the small average value.

TABLE II
Extracted Parameter Values of HEMT's-on-Si

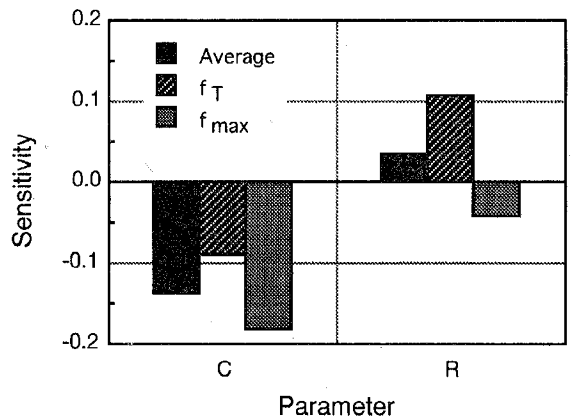
Parameters	Values
Gm (mS)	43
td (ps)	1.6
Cgs (pF)	0.28
Rin (Ω)	0.0
Cds (pF)	0.20
Csub (pF)	0.17
Cgp (pF)	0.29
Rgp (Ω)	39
Cdp (pF)	0.23
Rdp (Ω)	35
Cgd (pF)	0.044
Cb (pF)	0.045
Rds (Ω)	310
Rg (Ω)	14
Rs (Ω)	0.9
Rd (Ω)	12

This result indicates that the crucial problem which degrades the performance of HEMT's-on-Si is large capacitances such as the pad capacitance, C_{gp} and C_{dp}, and the drain-source capacitance, C_{ds}. Decreasing them is the most important improvement of HEMT's-on-Si. The results also mean that the resistivity of the Si substrate used is not an important factor, and that specially ordered Si substrate with a higher resistivity than widely used is not required.

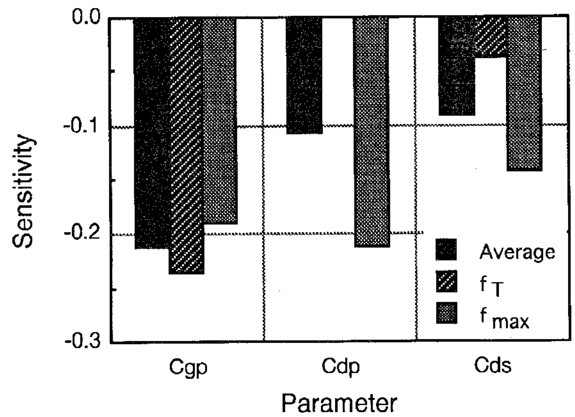
To clarify which capacitance, C_{gp}, C_{dp}, and C_{ds}, is dominant, their sensitivities are compared in Fig. 7(b). The most dominant capacitance is C_{gp}. The second dominant is C_{dp}. This result indicates that the most important for the good microwave performances of HEMT's-on-Si is decreasing the gate-pad capacitances.

C. Improvement of HEMT's-on-Si

To improve the microwave characteristics of HEMT's-on-Si, the silicon dioxide (SiO_2) film was inserted between the gate and drain pads and the buffer layer. The thickness of the film is 3000 Å [21]. The (extracted) pad capacitances of devices with and without the SiO_2 insertion are compared in Table III. The reductions of C_{gp} and C_{dp} were 53% and 42%, respectively. The measured f_T's and $f_{\max}$'s of devices



(a)



(b)

Fig. 7. Sensitivities of substrate-influenced parameters of HEMT's-on-Si to microwave characteristics. (a) Comparison of capacitances and resistances. (b) Comparison of the three capacitances.

TABLE III
COMPARISON OF EXTRACTED PAD CAPACITANCES, f_T'S AND $f_{\max}$'S OF HEMT's-on-Si WITH AND WITHOUT THE IMPROVEMENT

	Without Improvemt.	With Improvemt.
Cgp (pF)	0.29	0.13
Cdp (pF)	0.23	0.14
f_T (GHz)	11.7	19.7
f_{max} (GHz)	12.2	21.5

with and without the improvement are also compared in Table III. The increases in f_T and $f_{\max}$ were 68% and 76%, respectively. This result was consistent with the suggestion in the previous section that reducing the pad capacitances leads to the improvement of the microwave performance of HEMT's-on-Si.

It was observed that the pad capacitances varied with the bias conditions for the device without the improvement as shown in Table IV, resulting from the fact that the pads were directly placed on the buffer layer. The large increase of C_{gp} for the normal bias is due to the Schottky contact between aluminum and AlGaAs, and degrades the microwave performance. The variations were not observed for the improved device, as also shown in Table IV. The insertion of silicon dioxide has reduced not only the pad capacitances but also the capacitance variations with the bias, especially the increase in C_{gp}. It has made a great contribution to the better microwave performance.

TABLE IV
VARIATIONS OF EXTRACTED PAD CAPACITANCES WITH BIAS CONDITIONS OF HEMT's-on-Si WITH AND WITHOUT THE IMPROVEMENT

	Without Improvemt.	With Improvemt.
Cgp (pF)		
at normal bias	0.29	0.13
at 'cold' bias	0.24	0.13
Cdp (pF)		
at normal bias	0.23	0.14
at 'cold' bias	0.24	0.14

VI. CONCLUSION

A new small-signal linear equivalent circuit for high electron mobility transistors fabricated on GaAs-on-Si wafers, HEMT's-on-Si, has been proposed. Influences of the pads, the GaAs-Si interface, and the Si substrate on the microwave characteristics are included, and pads are expressed by series connections of resistors and capacitors in the circuit. The new equivalent circuit describes the microwave characteristics of HEMT's-on-Si with the error of 6%. It also has a great advantage in that it can separately analyze the intrinsic device characteristics and influences of Si substrate and GaAs-Si interface.

Analyses using the new equivalent circuit show that the crucial problem of HEMT's-on-Si is the larger values of the pad capacitances than those of HEMT's-on-GaAs, and that decreasing the capacitances, especially the gate-pad capacitance, is the most important improvement. This is proved by the device improvement. The analyses show also that the substrate resistivity is not so important for microwave performances of HEMT's-on-Si, and that there is no need to worry about it.

This circuit is also applicable to MESFET's-on-Si.

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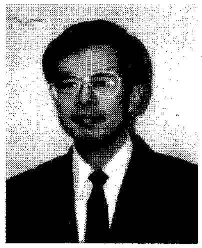

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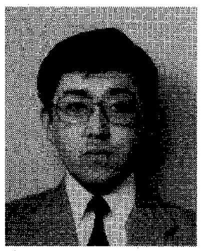

Takashi Aigo received the B.E. and M.E. degrees in electrical engineering from Tohoku University, Sendai, Japan in 1981 and 1983, respectively.

From 1983 to 1990 he was with Fujitsu Ltd., where he worked in the area of the processing and evaluation for GaAs MESFET's and HEMT's. He joined the Advanced Technology Research Laboratories of Nippon Steel Corporation in 1990 and he has been involved in the research for the application of GaAs on Si to electronic devices.

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From 1972 to 1985 he was a Research Associate and an Assistant Professor at the Department of Electronic Engineering of Osaka University, working in the area of modulation spectroscopy and other optical characterizations of semiconductors. He joined the Advanced Technology Research Laboratories of Nippon Steel Corporation in 1985 and has been engaged in the research and development of MOCVD growth of GaAs on Si and the application of GaAs-on-Si to electronic devices. He is a Chief Researcher in the Laboratories.