

# A New Field-Effect Transistor with Selectively Doped $GaAs/n - Al_xGa_{1-x}As$ Heterojunction

Discussie & kwalitatieve analyse

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## 1 Inleiding

Het artikel dat behandeld wordt, “A New Field-Effect Transistor with Selectively Doped  $GaAs/n - Al_xGa_{1-x}As$  Heterojunction”, is geschreven door Takashi Mimura, Satoshi Hiyamizu, Toshio Fuji en Kazuo Nanbu in 1980. Het artikel is gepubliceerd in het Japanese Journal of Applied Physics (JJAP). Alle artikelen in dit paper zijn gepeer-reviewed. Het artikel borduurt voort een artikel an Dingle et al (Bell Laboratories): “Electron mobilities in modulation-doped semiconductor heterojunction superlattices”.

Het artikel is gepubliceerd dit in opdracht van Fujitsu Laboratories Ltd. Fujitsu was geïnteresseerd in het vercommercializeren van de ontdekking die gedaan is door Dingle. Nadat Dingle zijn onderzoek had gepubliceerd ontstond er namelijk een ware race om de eerste te zijn die deze technologie werkend te krijgen.

Er is een patent van Daniel Delagebeaudeuf en Trong L Nuyen, “Field effect transistor with a high cut-off frequency”. Dit patent borduurt voort op het werk van Mimura et al. en Dingle et al. Beide waren werkzaam bij Thomson-CSF. Dit lab was in staat waren een betere variant van de transistor te fabriceren.

De abstract is duidelijk om geeft meteen aan waarom dit nieuwe type FET interessant is. De reden is dat deze FET veel (tot 3x) hogere frequenties aankan dan de huidige ontwerpen.

In de inleiding wordt duidelijk gemaakt dat dit artikel voortborduilt op het artikel van Dingle et al. In dit artikel wordt een nieuw fenomeen gerapporteerd, namelijk de hogere mobiliteit van elektronen in  $AlGaAs/GaAs$  heterojunction. In dit artikel wordt verder gegaan met deze ontdekking en wordt gekeken hoe deze hogere mobiliteit gebruikt kan worden in nieuwe halfgeleider componenten. Deze inleiding geeft een goed beeld van de context waarin het artikel geschreven is.

## 2 Discussie

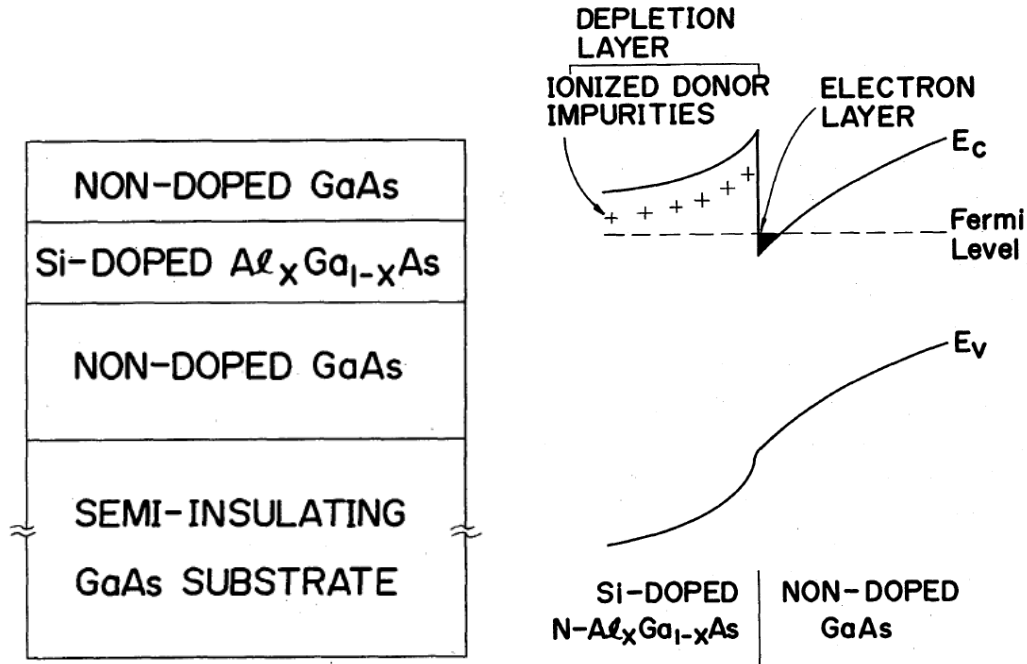
De hoofdvraag van dit artikel is: “Kan de hogere elektronmobiliteit van een heterojunction gebruikt worden voor het fabriceren van een snellere transistor?”. Deze hoofdvraag wordt experimenteel bevestigd door het creëren van onder andere transistoren, diodes en hall-bruggen en het testen hiervan.

Om deze vraag te beantwoorden is gekozen voor een kwantitatieve onderzoeksmethode. Om te kijken of het mogelijk was om transistoren te maken zijn deze eerst gefabriceerd, waarna deze getest zijn. Hierbij werd specifiek gekeken of deze dezelfde verschijnselen vertonen als die uit het voorgaande onderzoek van Dingle et al. Daarna zijn de karakteristieken van deze nieuwe transistor vergeleken met een andere type transistor dat hetzelfde doel heeft.

De resultaten van de testen bevestigen de voorgaande bevindingen van Dingle et al. en wijzen erop dat er een 2-dimensionaal elektrongas ontstaat. Ook wordt aangetoond dat het mogelijk is om het elektrongas te moduleren door het drain-voltage  $V_{DS}$  op de transistor te variëren. Deze resultaten zijn belangrijk omdat hiermee de onderzoeksvraag beantwoord kan worden. Ook kan uit deze resultaten afgeleid worden dat dit nieuwe transistorontwerp, op hoge frequenties, inderdaad beter werkt dan andere ontwerpen.

### 3 Resultaten

In het artikel worden verschillende testen gedaan om te controleren of de transistor werkt zoals wordt verwacht. In de figuren 1a en 1b wordt toegelicht hoe de heterojunction die getest is, is opgebouwd. Hierbij gekeken naar zowel de fysieke structuur (figuur 1a) als naar de bandenstructuur (figuur 1b). In figuur 2 wordt gekeken of het effect van het 2-dimensionaal elektrongas gereproduceerd kan worden en hoe sterk dat is.



(a) De fysieke opbouw van de getestte heterojunction

(b) Opbouw van de bandenstructuur van de getestte heterojunction

#### 3.1 Figuur 1a

In figuur 1a wordt de fysieke opbouw van de getestte heterojunction schematisch weergegeven. In de tekst wordt toegelicht wat de afmetingen van de lagen zijn en hoe sterk deze gedoteerd zijn.

Ook wordt aangegeven dat deze structuur gecreeërd is met behulp van MBE (molecular beam epitaxy). Dit is een manier om hoogkristalliene lagen aan te brengen op een substraat.

#### 3.2 Figuur 1b

In figuur 1b wordt gekeken naar de elektrische bandenstructuur van de heterojunction. In dit diagram wordt geïllustreerd hoe de bandenstructuur ervoor zorgt dat er een 2-dimensionaal elektrongas ontstaat.

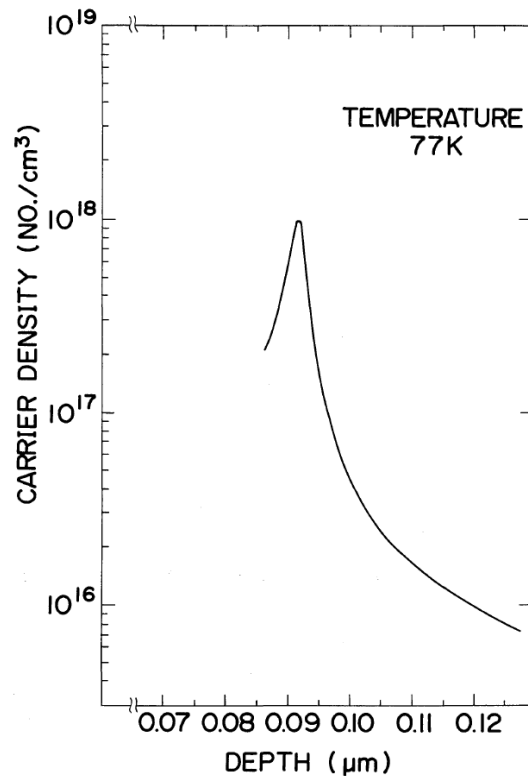
Er wordt in het artikel weinig ingegaan op waarom er sprake is van “electron-confinement” en waarom de elektronen van de donor naar de GaAs-laag migreren. Dit wordt kort aangestipt in de introductie van het artikel. Hier wordt verwezen naar de metingen van Dingle et al. en uitgelegt dat de elektronen naar de GaAs-laag migreren omdat deze een hogere “elektronenaffiniteit” heeft. Dit houdt in de elektronen makkelijker kunnen bewegen in de GaAs-laag, omdat ze hier niet afgeremd worden door de donoronzuiverheden.

### 3.3 Figuur 2

In figuur 2 wordt de “apparent carrier profile” weergegeven zoals gemeten op 77K. De “apparent carrier profile” geeft aan wat de lading (elektronen)dichtheid is op een bepaalde diepte van het substraat.

Dit dichtheidsprofiel is gemeten met behulp van een “differential capacitance feedback profiler”. Door een voltage over de heterojunction te zetten en dan capaciteit te bepalen kan volgens Kroëmer et al. bepaald worden hoeveel ladingdragers er aanwezig zijn op een bepaalde diepte.

De duidelijk waarneembare piek kan duiden op de aanwezigheid van een 2-dimensionaal elektrongas.



Figuur 2: Dichtheid van ladingdragers als functie van de doorsnee van de heterojunction. Er is een duidelijk waarneembare piek die kan mogelijk ontstaan door de aanwezigheid van een 2-dimensionaal elektrongas

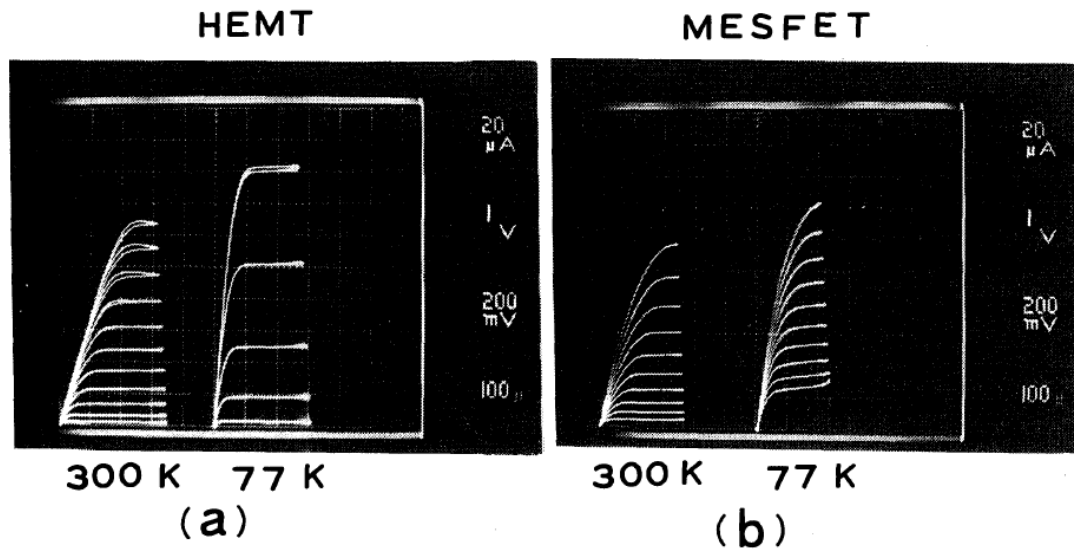
### 3.4 Figuur 3

In figuur 3 wordt het stroom-voltage-karakteristiek van het nieuwe type transistor vergeleken met een bestaand type transistor op 300K en op 77K. Er wordt duidelijk toegelicht wat de afmetingen van de heterojunction zijn en op welke voltage en amperage er gemeten is. Ook wordt duidelijk aangegeven wat de schaal is van het grafiek.

Uit de grafieken is duidelijk af te leiden dat het nieuwe type transistor (figuur 3a) voornamelijk op lage temperaturen een veel betere geleiding heeft dan op hogere temperatuur. Dit is voornamelijk om dat de elektronmobiliteit toeneemt op lage temperaturen. Dit is te zien aan de grotere spreiding tussen de lijnen in figuur 3a. Deze lijnen drukken

de waarden uit in geleiding ( $G_m$ ) of wel  $1/R$ . In het artikel wordt daarna aangetoond dat een beter geleiding direct te vertalen is naar een hogere bandbreedte voor de transistor.

De onderzoekers hebben geprobeerd om de vergelijkingstransistor zoveel mogelijk hetzelfde te krijgen als het nieuwe type. De nieuwe HEMT-transistor heeft, zoals te zien in figuur 2, rond de heterojunction een ladingdichtheid van minimaal  $\pm 2 \cdot 10^{17}/\text{cm}^3$ . De MESFET waarmee vergeleken wordt is daarom zo gedoteerd dat deze een ladingdichtheid van  $1.0 \cdot 10^{17}/\text{cm}^3$  heeft. Ook is geprobeerd om de gate-, source- en drain-geometrie hetzelfde te houden zodat deze dezelfde capaciteit hebben.



Figuur 3: Vergelijking van de stroom-voltage-karakteristiek van een HEMT-FET(a) en een MESFET(b)

## 4 Experimenten

Voor het testen van het nieuwe type transistor zijn 2 testen gedaan: capaciteit-voltage-profilering en stroom-voltage-karakteristiek bepaling.

### 4.1 Capaciteit-voltage-profilering

Capaciteit-voltage-profilering of CV-profilering is een techniek die gebruikt wordt om de interne structuur van een heterojunction te bepalen. Door een spanning over de heterojunction te zetten wordt een “depletion-region” gecreeërd. Deze bevat geen elektronen of gaten meer, maar heeft nog wel een intrinsieke lading vanwege de aanwezig donoratomen. Deze intrinsieke lading creeërt een capaciteit die meetbaar is. Door de spanning over de heterojunction te variëren kan de “depletion-region” groter of kleiner gemaakt worden, waardoor gekeken kan worden naar verschillende delen van de heterojunction.

De resultaten van deze test zijn te vinden in figuur 2 van het artikel. In dit grafiek is de gemeten capaciteit omgezet naar een ladingsdichtheid.

### 4.2 Stroom-voltage-karakteristiekbepaling

De stroom-voltage-karakteristiek of IV-curve is een manier waarop de parameters van een transistor bepaald kunnen worden. Door een vaste stroom aan te bieden op de gate (of base) van een transistor en de spanning over de source-drain of (collector-emitter) te variëren kan bepaald worden wanneer de transistor volledig “aan” is en hoe lineair de versterking is van de transistor. Ook kan de zogenaamde “small-signal applification” of  $H_{fe}$  bepaald worden.

## 5 Referenties

Het artikel gebruikt de ACS of “American Chemical Society”-referentiestijl. Deze stijl volgt het volgende format: Achternaam, Initialen.; Achternaam, Initialen. tijdschrift. jaar, Volume, paginas.

Alle referenties in het artikel komen slechts 1 keer voor, maar het belangrijkste artikel is het eerst vermeldde artikel: “Electron mobilities in modulation-doped semiconductor heterojunction superlattices”. De wetenschappers hebben namelijk geprobeerd om de nieuwe bevindingen uit dit artikel te reproduceren en toe te passen en in nieuw type transistor.

## A New Field-Effect Transistor with Selectively Doped GaAs/n-Al<sub>x</sub>Ga<sub>1-x</sub>As Heterojunctions

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Studies of field-effect control of the high mobility electrons in MBE-grown selectively doped GaAs/n-Al<sub>x</sub>Ga<sub>1-x</sub>As heterojunctions are described. Successful fabrication of a new field-effect transistor, called a high electron mobility transistor (HEMT), with extremely high-speed microwave capabilities is reported.

One of the most interesting phenomena in heterojunction structures is the mobility enhancement behavior first reported by Dingle *et al.*<sup>1)</sup> in MBE (molecular beam epitaxy)-grown modulation-doped GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As superlattices. In these structures, alternate layers of GaAs and Al<sub>x</sub>Ga<sub>1-x</sub>As with the Al<sub>x</sub>Ga<sub>1-x</sub>As layers selectively doped with Si are involved. Because of the higher electron affinity of GaAs, free electrons in Al<sub>x</sub>Ga<sub>1-x</sub>As layers are transferred to the non-doped GaAs layers where they form a quasi two-dimensional Fermi gas. The measured Hall mobilities parallel to the layers are higher than that of uniformly doped GaAs of equivalent doping concentration. The mobility enhancement behavior is attributed to the spatial separation between electrons and their parent donor impurities. In this paper we report our studies of field-effect control of the high mobility electrons in selectively doped GaAs/n-Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures and describe fabrication of a new field-effect transistor, called a high electron mobility transistor (HEMT), with extremely high-speed microwave capabilities.

The heterostructure used in this experiment consists of non-doped GaAs epilayers and a Si-doped n-type Al<sub>x</sub>Ga<sub>1-x</sub>As ( $x=0.32$ ) epilayer, as illustrated in Fig. 1(a). The epilayers, 1  $\mu\text{m}$  thick, were grown successively by MBE on a Cr-doped semi-insulating GaAs substrate. The doping level in Al<sub>x</sub>Ga<sub>1-x</sub>As is  $6.6 \times 10^{17}/\text{cm}^3$ . A schematic energy band diagram of a non-doped GaAs/n-Al<sub>x</sub>Ga<sub>1-x</sub>As heterojunction is shown in Fig. 1(b). An electron layer is formed at the GaAs side of the interface, while the

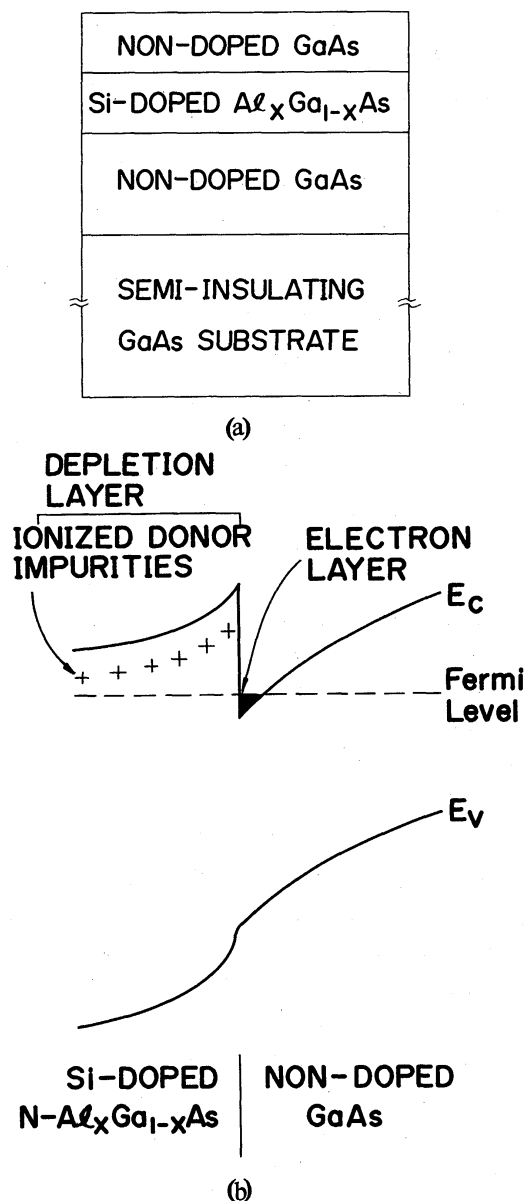


Fig. 1. (a) Heterostructure used in field-effect experiments. (b) Schematic energy band diagram of a selectively doped GaAs/n-Al<sub>x</sub>Ga<sub>1-x</sub>As heterojunction.



$\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer is depleted towards the interface.

Device fabrication starts with the etching of mesa islands down to the non-doped GaAs layer adjacent to the semi-insulating substrate to localize the active region. The source and drain ohmic contacts are made with gold-germanium eutectic alloy and gold overlay. Rectifying contact for the gate is provided by the deposition of aluminum on the surface of non-doped GaAs of the top epilayer. We have simultaneously fabricated HEMT's, Hall bridges and diodes for capacitance-voltage measurements in the wafer.

Figure 2 shows the apparent carrier profile measured at 77 K with a differential capacitance feedback profiler. Simple profiling theory suggests that the obtained carrier profile should give the true electron distribution except for minor Debye-length smearing.<sup>2)</sup> In the case of GaAs for carrier concentrations of  $10^{17}$  and  $10^{18}/\text{cm}^3$ , the Debye lengths at 77 K are 68 and 21 Å, respectively. In Fig. 2 we can observe a spike-like carrier profile with the spreading width of 85 Å at the carrier concentration of  $2 \times 10^{17}/\text{cm}^3$ . The spike-like carrier profile may result from the two-dimensionality of electrons confined to the GaAs layer. The two-dimensionality of the electron layers was first demonstrated by Shubnikov-de Haas measurements in modulation-doped superlattices.<sup>3)</sup>

Figure 3(a) shows 300 K and 77 K drain current-voltage characteristics of the HEMT, measured with a 100 Hz curve tracer. Complete pinch-off of the drain current from the gate is observed. The drain current saturates at the drain voltage  $V_{\text{DS}}$  where  $V_{\text{DS}} = V_{\text{GS}} - V_{\text{p}}$ , as expected from the Shockley model.<sup>4)</sup> Here  $V_{\text{GS}}$  represents the source-to-gate voltage and  $V_{\text{p}}$  the pinch-off voltage. In Fig. 3(a) we can observe a dramatic increase in saturated transconductance  $G_{\text{m}}$  by a factor as much as 3, when the HEMT is cooled to 77 K. This increase in  $G_{\text{m}}$  is partly due to the increase in the electron mobility at low temperatures. The Hall mobility measured at 77 K was  $32500 \text{ cm}^2/\text{V}\cdot\text{s}$ , which is higher than what has been reported in modulation-doped superlattices.

Conventional Schottky-gate GaAs field-effect transistors (MESFETs) were fabricated using VPE (vapor phase epitaxy)-grown active layer with the carrier concentration of  $1.0 \times 10^{17}/$

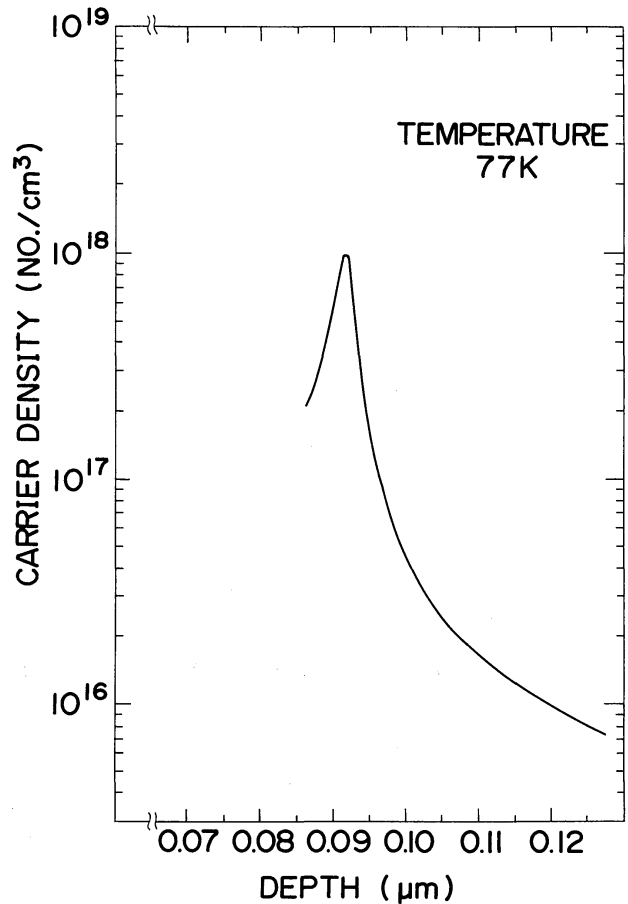


Fig. 2. Carrier profile obtained for the heterostructure at 77 K.

$\text{cm}^3$ . The geometry and zero gate-bias drain saturation current of the MESFETs are the same as those for the HEMT.

Figure 3(b) shows 300 K and 77 K drain current-voltage characteristics of the MESFETs. In contrast to the HEMT, the MESFET does not exhibit any significant increase in 77 K transconductance.

In Table I we compare the parameters of the HEMT with those of the GaAs MESFET. The 300 K mobility of the HEMT is 30 percent higher than that of the MESFET. The mobility advantage of the HEMT over the MESFET increases by a factor of 5 to 6 by lowering the temperature to 77 K. 77 K transconductance of the HEMT is 3 times higher than that of the MESFET. The intrinsic high-speed capability of the transistor depends on the current gain-bandwidth product  $f_{\text{T}}$ , which is given by  $f_{\text{T}} = G_{\text{m}}/2\pi C_{\text{GS}}$ . Here  $C_{\text{GS}}$  denotes the gate-to-source capacitance. If we assume that the  $C_{\text{GS}}$  values for the HEMT and the MESFET of the same geometry are similar, high-speed capabilities depend principally on the  $G_{\text{m}}$  values.

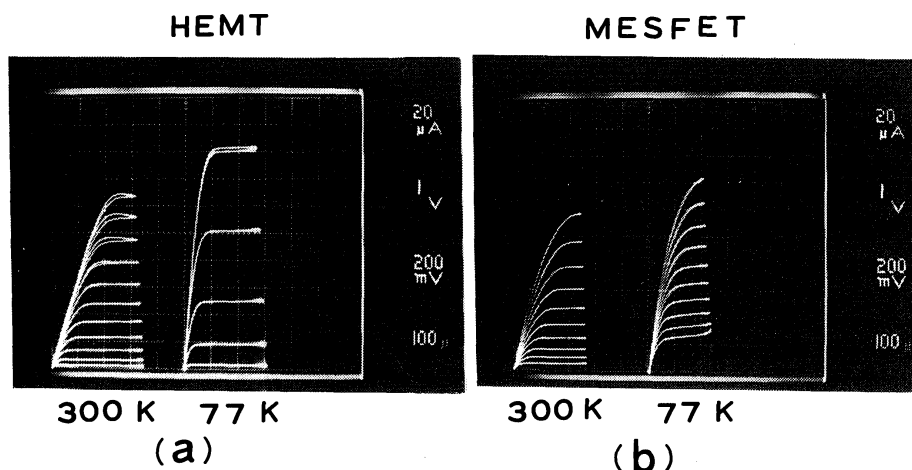


Fig. 3. 300 K and 77 K current-voltage characteristics of the HEMT (a) and the GaAs MESFET (b). Both devices have the same geometrical dimensions: Gate length=400  $\mu\text{m}$ , Gate width=50  $\mu\text{m}$ . Scales: Drain current, 20  $\mu\text{A}/\text{div.}$ ; Drain voltage, 1 V/div.; Gate voltage, 0.2 V/step.

Table I. Parameters of the HEMT and the GaAs MESFET.

	Carrier concentration	Hall mobility, $\mu_H$ ( $\text{cm}^2/\text{V}\cdot\text{s}$ )		Mobility advantage at 77 K, $\mu_H(\text{HEMT})/\mu_H(\text{MESFET})$	Transconductance advantage at 77 K, $G_m(\text{HEMT})/G_m(\text{MESFET})$
		300 K	77 K		
HEMT	$0.7 \times 10^{12}/\text{cm}^2$	6200	32500	5.5	3
MESFET	$1.0 \times 10^{17}/\text{cm}^3$	4700	5800		

Therefore the HEMT should attain 3 times higher speeds than the MESFET at 77 K.

Recent calculations have predicted that the maximum attainable mobility at low temperature limited by Coulomb scattering from donor ions should exceed  $10^5 \text{ cm}^2/\text{V}\cdot\text{s}$ .<sup>5)</sup> The HEMT with improved electron mobility may attain at least 10 times higher speed than the GaAs MESFET.

In summary, we have described a new field-effect transistor, called a high electron mobility transistor (HEMT), with selectively doped GaAs/n-Al<sub>x</sub>Ga<sub>1-x</sub>As heterojunctions. 77 K and 300 K mobilities of the HEMT are significantly higher than those of the GaAs MESFET with similar drain saturation current. Dramatic increase in transconductance of the HEMT has been observed when the HEMT was cooled to 77 K. Crude estimation has shown that the

high-speed performance of the HEMT should be 3 times superior to that of the MESFET at 77 K. Further substantial improvements in high-speed capability of the HEMT are expected with improved electron mobilities at low temperatures.

The authors would like to thank to M. Fukuta and T. Hashimoto for supporting this work.

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# Electron mobilities in modulation-doped semiconductor heterojunction superlattices

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GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As superlattice structures in which electron mobilities exceed those of otherwise equivalent epitaxial GaAs as well as the Brooks-Herring predictions near room temperature and at very low temperatures are reported. This new behavior is achieved via a modulation-doping technique that spatially separates conduction electrons and their parent donor impurity atoms, thereby reducing the influence of ionized and neutral impurity scattering on the electron motion.

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Synthetic semiconductor superlattice structures are of both fundamental and technological interest. Most suggestions concerning the growth of such structures focus on either a multilayer heterojunction arrangement<sup>1,2,4</sup> or a periodic alternation of the doping of only one semiconductor to form a series of homojunctions.<sup>3-5</sup> Molecular-beam epitaxy (MBE) is known<sup>6</sup> to produce atomically smooth layers and to allow very precise control over grown layer thickness. In particular, these features have been utilized in the production of multilayer heterojunction superlattices of GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As<sup>1,2</sup> and other semiconductor combinations.<sup>7,8</sup> Layer thicknesses on the order of atomic dimensions have been routinely<sup>9</sup> achieved. Typical unintentionally doped GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As structures are thought to be lightly *p* type,<sup>1</sup> whereas deliberate uniform doping can produce superlattices with  $n \sim 10^{18} \text{ cm}^{-3}$ .<sup>10-12</sup> In this doping range, mobilities significantly greater than  $\mu \sim 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$  are difficult to achieve. Such mobilities, which are considerably below the Brooks-Herring-Dingle predictions<sup>13</sup> for uncompensated GaAs at this concentration, severely limit the usefulness of these structures.

In this letter, we wish to report the growth and properties of *heterojunction* superlattices of GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As in which the independent notion of *modulation doping* is incorporated. Resultant Hall mobilities (300 K) for electrons are larger than any yet reported for either uniformly doped GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As superlattices, equivalently doped MBE-grown bulk GaAs, or equivalently doped GaAs grown by other means. Moreover, the 300 K mobilities are usually greater than the upper limit predicted by the Brooks-Herring-Dingle theories of electron mobility in bulk *n*-type GaAs. At temperatures below 50 K a dramatic increase over the mobilities of uniformly doped *n*-type heterojunction superlattices and bulk GaAs of equivalent electron concentration is obtained.

The structures were grown in an MBE system described earlier<sup>1,9</sup> with the modification that a silicon doping source, which could be abruptly initiated or terminated, was included. Uniformly doped multilayer heterojunctions were grown with a calibrated Si beam impinging continuously on the sample. These structures

are *n* type with room-temperature mobilities in the  $1000\text{--}2500\text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$  range. Depending on the doping level, mobilities are either essentially temperature independent ( $n \sim 10^{17}\text{--}10^{18} \text{ cm}^{-3}$ ) or else they decrease strongly on cooling ( $n < 10^{17} \text{ cm}^{-3}$ ).

Modulated doping is achieved by synchronization of the Si and Al source fluxes so that only the Al<sub>x</sub>Ga<sub>1-x</sub>As layers are deliberately doped with Si impurities. In a second version, the Si beam is shuttered in such a way that up to 60 Å of each side of every Al<sub>x</sub>Ga<sub>1-x</sub>As layer are not intentionally doped, thus keeping the Si dopant away from the interface region. If, as we believe, Si diffusion is negligible at the growth temperature of  $\sim 600^\circ \text{C}$ , then in each structure the GaAs layers will contain only unintentional background impurities ( $10^{14}\text{--}10^{15} \text{ cm}^{-3}$  range).

Figure 1 presents a model for the conduction band edge structure of a uniformly doped (UD) and a modulation-doped (MD) superlattice. Si donors are distributed according to the appropriate doping method. Typically  $x \approx 0.3$  in Al<sub>x</sub>Ga<sub>1-x</sub>As, leading to  $\Delta E_c \approx 300 \text{ meV}$ . The binding energy of isolated Si donors in bulk GaAs is

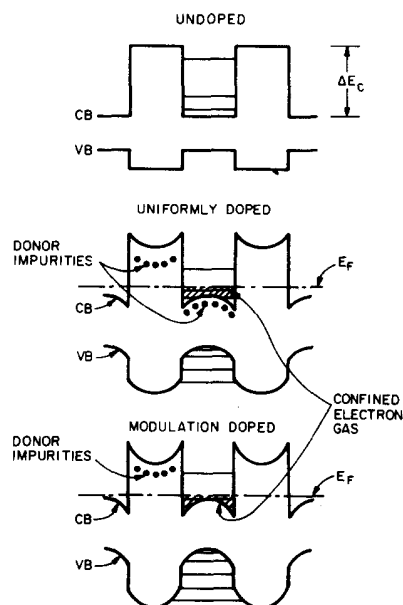


FIG. 1. Energy-band diagrams for *n*-doped and undoped GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As superlattices.

<sup>a)</sup>On leave from the High Field Magnet Laboratory of the Max-Planck-Institute in Grenoble, France.

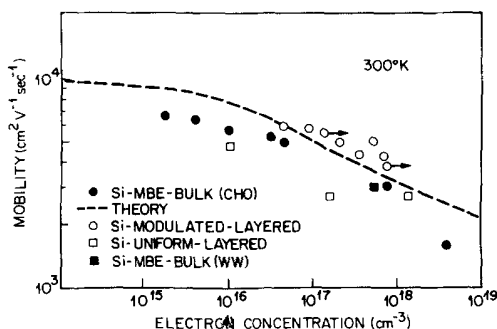


FIG. 2. 300 K mobilities of a range of Si-doped GaAs and Si-doped GaAs- $\text{Al}_x\text{Ga}_{1-x}\text{As}$  superlattices. The filled circles and the theory [Brookes-Herring,  $(N^+ + N^-)/n = 1$ ] are taken from Ref. 6. The horizontal arrows show electron concentration changes discussed in the text.

$E_{D,\text{Si}}^{\text{GaAs}} \sim 6$  meV, whereas in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  it has been suggested that Si can introduce a dominant deep donor with  $E_D \sim 100$  meV or larger. Lang *et al.*<sup>14</sup> believe that this deep donor merges with the conduction band at  $x \leq 0.35$  and so, in the present case, we expect that  $\Delta E_c \gg E_D$ .<sup>15</sup> Since the GaAs conduction band edge lies lower in energy than the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  donor states, electrons from the donors will move into the GaAs regions. For both UD and MD structures the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  regions are depleted in order to satisfy the requirement of a continuous Fermi level throughout each superlattice, which in turn leads to appreciable band bending (which is impurity-concentration and layer-thickness dependent). This is depicted in a qualitative manner in Fig. 1. In both UD and MD superlattice structures the carriers confined to the GaAs layer will form a pseudo-two-dimensional electron gas (2DEG).

The most important feature of the MD structure is that essentially all of the mobile carriers (electrons confined to the GaAs layer) and their parent donor impurities (in the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer) are spatially separated from each other in an irreversible manner. Thus the electron density in the GaAs channel may greatly exceed the density of the unintentionally present (neutral and ionized) impurity scattering centers in the channel, leading to considerable change in mobility behavior in the temperature and carrier density regimes where impurity scattering mechanisms are important. In many respects the situation resembles that in a Si-MOSFET where the 2DEG concentration is also independent of the doping level in the channel. To a much smaller degree, mobility enhancement could also occur in UD structures, although in the range of UD superlattices that we have studied, mobility enhancement has not been observed. A periodic doping of a single semiconductor material to form a chain of  $(nipi)_m$  regions<sup>3-5</sup> would have the opposite effect to that of modulation doping, namely, the mobile electrons (holes) would be restrained to the same spatial region as their parent donor (acceptor) impurity. Enhanced mobility behavior is not anticipated.

Figure 2 compares 300 K mobilities of MBE-grown GaAs samples of differing carrier concentration with those of UD and MD GaAs- $\text{Al}_x\text{Ga}_{1-x}\text{As}$  superlattices. The Hall mobilities in the MD structures are as much

as a factor of 2 greater than the mobilities of electrons in UD superlattices or in GaAs of equivalent electron concentration. If essentially all of the electrons contributing to the conduction process are considered to be in the GaAs channels,<sup>16</sup> then the mobility is that of material containing almost twice as many carriers as derived using the total superlattice thickness—"bulk" GaAs approach. The resultant shift is shown in the data of Fig. 2. Variation of the layer thickness in the range 100–450 Å appears to have only a minor influence on these room-temperature mobilities.

Perhaps the most dramatic influence of modulation doping is in the temperature dependence of the mobility. In Fig. 3 we compare the mobility of a MD superlattice ( $n \sim 5 \times 10^{16} \text{ cm}^{-3}$ ), which is typical of MD structures, with a range of data from UD structures and an MBE GaAs sample. The mobility behavior of the latter in the  $< 100$  K range is mainly attributed to ionized impurity scattering.<sup>13</sup> In this regime the mobility should follow a  $T^{3/2}$  law.<sup>13,17</sup> The UD samples and the MBE-grown GaAs do show a  $T^{3/2}$  behavior although a good quantitative fit to the appropriate expression (including screening) using reasonable parameters is only possible for the bulk sample. In contrast, the MD samples should show strongly modified impurity scattering since the Coulomb interaction with ionized impurities responsible for the  $T^{3/2}$  scattering should be greatly reduced by the segregation of carriers and impurities. This yields a more metallic-like behavior, the mobilities showing a smooth increase with decreasing temperature. A detailed understanding of the mobility behavior in the 2DEG in these structures in terms of the modified two-dimensional impurity-scattering mechanism has not yet been achieved. From the preliminary information that we have, it appears that both UD and MD structures will require a detailed, but different treatment.

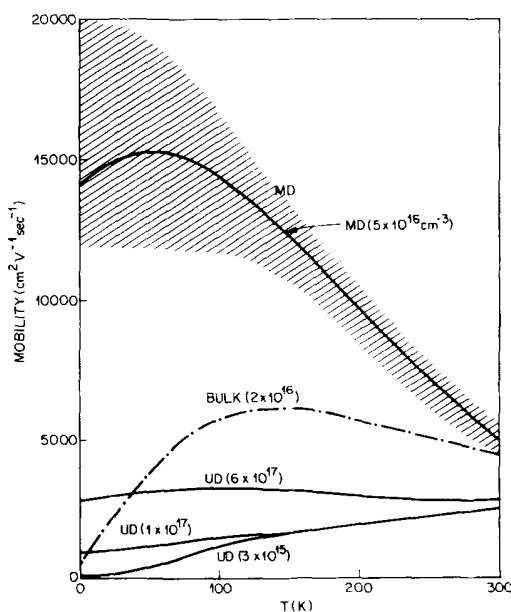


FIG. 3. Electron mobility versus temperature for bulk GaAs GaAs and several UD and MD superlattices. The crosshatched region includes most of the MD data.

In the doping range under consideration,  $n > 10^{18} \text{ cm}^{-3}$ , carrier freeze-out is not seen in any of UD or MD superlattices or in the MBE-grown bulk GaAs. This means that in MD superlattices one may expect electron concentrations as high as  $10^{18} \text{ cm}^{-3}$  with mobilities of at least  $10^4 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$  at liquid-helium temperatures. These low-temperature mobilities compare very favorably with those obtained at He temperatures from the very best CVD-grown GaAs<sup>13,18</sup> in which the carrier density is as much as  $10^{-5}$  smaller. A range of studies on these new structures is in progress. As an example of the low-temperature behavior of the 2DEG, we note that highly anisotropic oscillatory magnetoresistance behavior (Shubnikov-de Haas effect) has been seen at fields as low as 1 T, which is very much lower than data previously reported<sup>11</sup> for similar UD structures.

In summary, we have described MBE-grown, MD heterojunction superlattices of GaAs- $\text{Al}_x\text{Ga}_{1-x}\text{As}$  in which low-temperature and room-temperature electron mobilities can be significantly higher than those in equivalent GaAs material grown in other ways. At room temperature this may be valuable for a range of device structures, whereas, at temperatures below  $\sim 50 \text{ K}$ , mobilities of  $\geq 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$  and electron densities of up to  $\sim 10^{18} \text{ cm}^{-3}$  access a new range of fundamental and device possibilities.

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<sup>15</sup>Hall data from a bulk Si-doped  $\text{Al}_{0.26}\text{Ga}_{0.74}\text{As}$  layer indicates a deep level at  $E_D \sim 60 \text{ meV}$  as well as what appears to be a temperature-independent electron concentration of  $\sim 1.5 \times 10^{16} \text{ cm}^{-3}$  at low temperatures.

<sup>16</sup>Mobilities in MBE-grown  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  are low. In particular, the sample mentioned in Ref. 15 has a maximum mobility of  $\mu \approx 800 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$  at room temperature which falls to  $\mu \sim 10 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}$  at 4.2 K. In the superlattices, any carriers remaining in the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer will make an insignificant contribution to the conductivity, especially at low temperatures.

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## Angle-resolved photoemission measurements of band discontinuities in the GaAs-Ge heterojunction<sup>a)</sup>

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The conduction- and valence-band discontinuities for the (110) GaAs-Ge heterojunction have been measured as  $\Delta E_c = 0.50 \text{ eV}$  and  $\Delta E_v = 0.25 \text{ eV}$  by the angle-resolved ultraviolet photoemission (ARUPS) technique. These values are in good agreement with the theoretical predictions of Pickett *et al.*

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During the past ten years, much effort has been devoted to understanding the physical properties of Schottky barriers and heterojunctions.<sup>1</sup> In both systems,

the main effects originate at the interface; for example, it is well known that Schottky-barrier heights, as measured by capacitance voltage (C-V) or current-voltage (I-V) characteristics, are nearly independent of the metal's work function for covalent semiconductor-metal pairs. Several theoretical models have been suggested to account for this pinning of the Fermi energy ( $E_F$ ).<sup>2-4</sup> Recent results obtained with surface-sensitive techniques such as ultraviolet photoelectron spectroscopy (UPS),<sup>5,6</sup> partial yield spectroscopy,<sup>7</sup> and electron

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