

Description

Field of the Invention

This application pertains to the field of active semiconductor devices. In particular, it pertains to transistors in which a substantial fraction of the current is carried by hot electrons, including ballistic electrons.

Background of the Invention

It has been known for some time that a hot electron transistor, especially a ballistic transistor, could potentially be operated at frequencies in excess of those achievable with conventional (diffusive) transistors. See, for instance, T. E. Bell, *IEEE Spectrum*, February 1986, pp. 36-38. Various types of hot electron transistors (HET) have been proposed. This application is concerned with one particular class of HETs, namely, compound semiconductor HETs. For a brief review, see L. F. Eastman, *ibid.*, pp. 42-45.

Essentially all the prior art work on compound semiconductor HETs has been concerned with GaAs-based devices, and recently ballistic transport has indeed been observed in GaAs-based research devices. A. F. J. Levi et al, *Physical Review Letters*, Vol. 55(19), pp. 2071-2073; M. Heiblum et al, *Physical Review Letters*, Vol. 55(20), pp. 2200-2203 and M. I. Nathan et al, *IEEE Spectrum*, February 1986, pp. 45-47.

The ballistic transport was observed in devices having geometries that are thought to hold promise for implementation as a practical HET. The first type, frequently referred to as a planar doped barrier transistor (PDBT, see for instance, J. R. Hayes et al, *Electronic Letters*, Vol. 20(21), pp. 851-852) or "camel" transistor, J. M. Shannon, *IEEE Proceedings*, Vol. 128(9), pp. 134-140 (1981)) uses thermionic injection and comprises emitter, base, and collector, with an appropriately shaped potential barrier between emitter and base, and a second barrier between base and collector. The second type, which is referred to as a tunneling hot electron transfer amplifier (THETA, see for instance, M. Heiblum, *Solid State Electronics*, Vol. 24, pp. 343-366) differs from the first type in having tunnel injection into the base. See also EP-A-0 067 276, which discloses a transistor that uses tunnel injection into an upper energy valley in the base. Both of the above types are unipolar; however, bipolar HETs have also been proposed in GaAs/AlGaAs.

The flow of electrons from emitter to base is controlled in both types by varying the emitter/base barrier potential by means of an applied voltage V_{eb} . Similarly, the flow of electrons from the base to the collector can be controlled by means of an externally applied voltage V_{bc} between base and collector. Under normal operating conditions, V_{bc} reverse biases the base/collector junction. Electrons injected from the

emitter into the base have energy substantially greater than the thermal energy of the ambient electrons in the base. These "hot" electrons ideally traverse the base without undergoing significant scattering. If the base/collector barrier is caused to be lower than the hot electron energy then some of the hot electrons can cross the barrier, be transmitted through the depletion region of the collector, and enter the sea of conduction electrons in the collector.

As will be readily understood by those skilled in the art, various difficulties have to be overcome before a device of this type can function as a practical HET. Among these difficulties is quantum mechanical reflection of the hot electrons by the base/collector barrier, and space charge limited current. Probably the greatest obstacle, however, is the difficulty of achieving substantially complete hot electron transport through the base, and, desirably, also through the depletion region of the collector. Means for achieving further improvements in HET characteristics would be of considerable significance.

Definitions

Electron transport in a crystal is herein defined to be "ballistic" if, in addition to its possible interaction with an accelerating electric field, the electron interacts substantially only with the static part of the lattice potential. Electron transport thus may be ballistic even though the electrons undergo some small angle scattering and/or small energy change.

A conduction electron herein is considered to be a "hot" electron in a given semiconductor region if its energy E is substantially greater than E_F , the Fermi energy in the region. Typically, $E \geq E_F + 10k_B T$, where k_B is the Boltzmann constant, and T is the absolute temperature of the lattice.

A "hot electron" transistor (HET) is a transistor whose operative characteristics are in substantial part determined by the transport of hot electrons through the transit region of the transistor, with minimal scattering of the hot electrons in the transit region.

The "transit region" of a HET herein is that portion of the HET through which substantial hot electron transport takes place, or is intended to take place. For instance, in a PDBT, camel transistor, or THETA device, the transit region consists of the base and the collector depletion region. In order to have the possibility of significant hot electron transport in a HET, the width of the transit region has to be less than the mean-free path of the hot electrons in the material.

The "ambient" charge carriers are those charge carriers (electrons or holes) that are essentially in thermal equilibrium with the lattice. For instance, in bipolar HETs the ambient charge carriers in the base typically are holes.

Summary of the Invention

With the invention as set out in the claims it is possible to provide

compound semiconductor HETs having substantial current gain (e.g., $\beta > 10$) at room temperature.

HETs of interest herein generally have geometries similar to those of prior art HETs. They comprise an electron emission region (the first region), an electron collection region (the third region), and a second region that is intermediate the first and third regions and forms interfaces therewith. The first region comprises an emitter layer, and the second region comprises a base layer, with typically the emitter layer contacting the base layer and forming the emitter/base interface therewith. The base layer is typically also in contact with third region material and forms the base/collector interface therewith. The first, second and third regions each generally consist of one or more layers of compound semiconductor material, with the composition of the base layer differing at least from that of the emitter layer. In some cases (e.g., in some bipolar HETs) the second region material may be basically the same as the third region material, with the second and third region materials containing different dopants and/or differing in dopant concentration.

HETs of interest herein also comprise means for making electrical contact with the first, second and third regions, respectively, and means for injecting hot electrons from the first into the second region. At least a substantial fraction (advantageously $> 90\%$) of the injected hot electrons transit the second region without substantial energy loss and cross the base/collector interface. The injected hot electrons have average energy E_i , and their average velocity may be different in the different regions. Furthermore, with the injected hot electrons is associated a crystal momentum vector k_i having a component $k_{i,1}$ perpendicular to, and a component $k_{i,2}$ parallel to, the emitter/base interface.

I have discovered that the characteristics of a HET can strongly depend on the materials used to construct the device. For instance, the emitter layer and the base layer advantageously consist of materials which have band structures such that the hot electrons injected into the base layer have trajectories that are substantially normal to the emitter/base interface, typically such that $k_{i,2}/k_{i,1}$ is less than about 0.2. This condition helps to ensure that a relatively large fraction of the injected electrons can transit the base layer without undergoing substantial scattering. This condition can typically be met if the emitter layer comprises an indirect, wide bandgap material such as AlSbAs, the base layer comprises material (exemplarily InAs) that has a conduction band centered on the Γ -point in k-space (the terminology used to describe the

band structure is conventional and well known to those skilled in the art), and the hot electrons are injected into these direct Γ -states.

Furthermore, the materials are most advantageously chosen such that the hot electron velocity component normal to the base/collector interface does not undergo substantial change upon crossing of that interface. This requires that the normal component of $\partial E_i / \partial k$ be substantially continuous (preferably changing by no more than about 20%) across the base/collector interface. In this expression E_i is the average energy of the hot electrons, k is the electron wave vector, and ∂ signifies the partial derivative. The condition ensures that quantum mechanical reflection and resonances due to the presence of the interface are minimized. In order for more than about 90% of the hot electrons to be transmitted in the forward direction through the interface, the velocity component normal to the interface (for electrons of energy E_i) should typically change by at most about 11% upon crossing of the interface, and in preferred embodiments of the invention this condition will be met. AlSb and InAs are exemplary emitter layer and base layer materials that can advantageously be used in a HET according to the invention.

There are other means that can optionally be employed to improve the characteristics of a HET. For instance, ensuring quantization of the occupied ambient conduction electron states in the base layer results in constraints on scattering and thus increases the probability that a hot electron can traverse the transit region ballistically. Such quantization results if at least one dimension of the base layer is very small, typically of the order of 10 nm. A very "thin" base layer that results in formation of a substantially 2-dimensional electron gas in the base layer introduces constraints on scattering, but a base layer that is not only thin but also narrow (and thus is substantially 1-dimensional) typically constrains scattering even further. Quantization of the ambient charge carriers in the base layer also increases the effective bandgap and thereby reduces the probability of interband scattering.

Incorporation of these and other features (to be discussed below) into a HET can result in a device having substantially improved performance, as compared to prior art devices. In particular, devices according to the invention can have room temperature $\beta \geq 10$ for a bias (V_{ce}) greater than about 1 volt.

More particularly, HETs according to the invention are disclosed in the appended claims.

Brief Description of the Drawings

FIG. 1 schematically depicts a device according to the invention;

FIG. 2 shows schematically some features of the conduction band structure of a device according

to the invention;

FIG. 3 schematically shows portions of the energy level diagrams of three materials useful in the practice of the invention; and

FIG. 4 gives room temperature current gain curves measured on an exemplary device according to the invention.

Detailed Description of Some Preferred Embodiments

FIG. 1 schematically depicts a HET 10 according to the invention, wherein 11, 12 and 13 are the first, second, and third regions, respectively, and 14, 15, and 16 are means for making electrical contact to the first, second, and third regions, respectively. It will be appreciated that in many cases the first and third regions can be identified with emitter and collector respectively, and typically each comprise more than one layer, and that the second region comprises the base layer. Portion 17 of the third region is a collector depletion region. Exemplarily, 11 comprises $\text{AlSb}_{0.92}\text{As}_{0.08}$, 12 consists substantially of InAs , and 17 and 13 comprise GaSb . Exemplarily, the base layer is about 10 nm thick.

FIG. 2 shows schematically the conduction band of a double heterojunction HET according to the invention under bias, with numerals 20, 21, and 22 referring to the first region, the base, and the third region, respectively. The arrow indicates the direction of flow of hot electrons, Φ_{eb} and Φ_{bc} are the emitter/base and base/collector energy barriers, respectively (associated with the emitter/base and base/collector interfaces, respectively), E_c is the quantum-mechanical confinement energy (due to the 2-dimensional nature of the electron gas in 21), and E_F is the Fermi energy in the second region. For the above referred to exemplary combination of materials, Φ_{eb} can be about 1.3 eV, and Φ_{bc} about 0.8 eV. Typically $\Phi_{bc} \geq 0.5$ eV for a room temperature HET.

Currently preferred embodiments use thermionic emission to inject hot electrons of average energy E_i from the emitter layer into the base layer. Space charging effects in the two barriers can be substantially avoided if the barrier regions are doped to a dopant density $p > j/e\bar{v}$, where e is the electron charge, j is the current density, and $\bar{v}$ is the average electron velocity in the respective barrier. Reverse current flow from the base to the emitter layer can be minimized by choosing Φ_{eb} to be substantially greater than the ambient thermal energy $k_B T$ (k_B is the Boltzmann constant, and T is the absolute temperature).

The injection of hot electrons into the base is in general most efficient if both energy and momentum parallel to the emitter/base interface are conserved. Thus the emitter layer and base layer are advantageously chosen such that there are in the base layer empty states at energy E_i , and that associated with

these empty states are wave vectors k_i that have components $k_{i,2}$ that are substantially equal to the corresponding wave vector component of the electrons of energy E_i in the emitter layer.

The above is schematically illustrated in FIGS. 3a and 3b, which show relevant portions of the band diagrams of exemplary emitter and base layer materials, respectively. As can be seen from FIG. 3a, electrons of energy close to E_i have in this emitter material (exemplarily AlSb) wave vectors close to the X-point in the Brillouin zone and thus, in a $\langle 100 \rangle$ oriented device, there are electrons occupying X-point minima with small $k_{i,2}$ ($k_{i,2} \ll \pi/a$), and other X-point minima with large $k_{i,2}$ ($k_{i,2} \sim \pi/a$, where a is the lattice constant of the emitter layer material). Similarly, FIG. 3b shows that electrons of energy close to E_i have in this base layer material (exemplarily InAs) wave vectors close to the Γ -point. This exemplary combination of emitter layer and base layer materials permits relatively efficient injection of hot electrons (of energy approximately equal to E_i) from the emitter layer into the base layer. In particular, the efficiently injected electrons are from the X-point minima with small $k_{i,2}$, which go into the small $k_{i,2}$ Γ -like states in the base layer material. Electrons from the other X-point minima cannot be efficiently injected because no empty states with large $k_{i,2}$ are available in the base layer material. Thus the injected electrons have only small velocity components parallel to the emitter/base interface, resulting in increased probability that the hot electrons can traverse the transit region ballistically.

A practical HET not only requires efficient injection of the hot electrons into the base but also substantially complete transmission of the hot electrons over the base/collector potential barrier. The probability that an electron is reflected at the base/collector interface decreases as the change of electron velocity upon entering the collector region decreases. Since the velocity is proportional to $\partial E / \partial k$, this suggests that advantageously the materials are selected such that $\partial E / \partial k_{E_{i,2}} \sim \partial E / \partial k_{E_{c,3}}$, where the partial derivatives are to be taken at the average energy of the hot electrons, and subscripts 2 and 3 refer to the materials on either side of the base/collector interface.

An approximate alternative expression of the velocity matching condition, derived from effective mass theory and introduced for illustrative purposes only, is $m_2^*/m_3^* \sim E_i / (E_i - \Phi_{bc})$, where m_2^* and m_3^* are the effective electron masses in the base and collector material, respectively. Thus, by careful choice of E_i , Φ_{bc} , base and collector materials (including the possible use of an appropriately designed superlattice in the collector depletion region), quantum reflections from Φ_{bc} can be minimized. Typically, such matching is possible for a relatively small range of electron energies (exemplarily about 0.5 eV). Thus, it is advantageous to choose the emitter material and Φ_{eb} such

that the injected electrons have a relatively small energy spread.

Furthermore, high transmission through the base/collector interface typically requires that the electron wave function in the collector be similar in character to that in the base (e.g., both be s-like for electrons of energy E_i). For instance the choice of InAs as base and GaSb as collector material makes possible satisfaction of both of the above matching conditions, as is illustrated by FIGS. 3b and 3c, in which the latter shows the relevant portion of the band diagram of an exemplary collector material (exemplarily GaSb). At energy E_i the electrons in both the base and the collector material are near the Γ -point in k-space and thus have s-like wavefunctions, and the slope of the conduction bands at E_i are similar in the two materials.

There are further means that may optionally be used to improve the operating characteristics of a HET according to the invention. For instance, I have found that in a device having dimensions such that the base region comprises quantized electron states there exist kinematical constraints (due principally to energy and momentum conservation) that reduce the probability of electron-scattering below that in the bulk. Thus it is advantageous to reduce at least one dimension of the base region (typically its thickness) such that the ambient charge carriers in the base behave in the manner of a quasi 2-dimensional charge carrier gas. Typically, this requires that the thickness is less than about 50 nm, preferably less than about 20 nm. Further reduction in the effective dimensionality of the ambient charge carrier gas can further reduce the scattering probability. For instance, application of a magnetic field normal to the base layer can result in a reduction of hot electron scattering by a substantial amount, exemplarily a factor of 2-10. As will be appreciated by those skilled in the art, such a magnetic field can impose lateral confinement on the charge carrier motion, resulting in an effectively 0-dimensional charge carrier gas. An effectively 1-dimensional charge carrier gas can be produced by means of a thin and narrow (e.g., < 50 nm) strip of base layer material.

It has also been found that electron scattering probabilities frequently depend strongly on the final state into which the electron is scattered. For instance, in InAs scattering of <100> directed hot electrons into L-minima is typically less likely than into X-minima. Therefore, the injection energy E_i is advantageously chosen to be less than the energy associated with the X-minima. On the other hand, it is not essential that E_i is also less than the energy associated with the L-minima. This discovery obviously results in greater design freedom, while maintaining low scattering of the hot electrons.

In HETs with two classes of mobile charge carriers (e.g., bipolar HETs) it is frequently desirable that

the effective heavy hole mass m_h^* be much greater than m_e^* , the effective electron mass, since this also gives rise to kinematic constraints on scattering. For this effect to be significant, it is typically desirable that $m_h^*/m_e^* \geq 10$ perpendicular to the base/collector interface. Exemplarily, this condition can be met by use of a strained base layer.

It will be obvious to those skilled in the art that all three regions of an inventive device will consist of single crystal material, and that the base layer is epitaxial with the adjoining materials. Such structures can be grown by known techniques, e.g., by molecular beam epitaxy.

In addition to the above referred to AlSbAs/InAs/GaSb structure a variety of other combinations of materials can be used in HETs according to the invention. Exemplary is a bipolar HET comprising an AlAs_{0.44}Sb_{0.56} emitter, a In_{0.53}Ga_{0.47}As base, and an InP collector.

Example I: On a (001)-oriented Te-doped (n^+) GaSb single crystal substrate was grown by MBE the following heteroepitaxial structure: a 800 nm thick n^+ Te-doped (10^{18}cm^{-3}) GaSb buffer layer, followed by a 350 nm thick Te-doped (10^{15}cm^{-3}) GaSb layer, the latter to become the collector depletion region. This was followed by a 10 nm thick modulation-doped InAs layer (to become the base layer), and a 150 nm thick Te-doped (10^{16}cm^{-3}) AlSb_{0.92}As_{0.08} layer (the latter to become the emitter layer). This in turn was followed by deposition of a 50 nm thick n^+ Te-doped (10^{18}cm^{-3}) AlSb_{0.92}As_{0.08} layer and of a 300 nm thick n^+ GaSb layer. After patterning the heterostructure (substantially in the manner shown in FIG. 1) by standard lithography and etching techniques, evaporated AuGeNi alloy contacts were made to the buffer layer, the base layer, and the uppermost layer, followed by rapid annealing to form ohmic contacts. Standard tests showed that the structure operated as a HET, with room temperature $\beta > 10$ for $V_{ce} \geq 1$ volt, as exemplified by the data presented in FIG. 4.

Example II: A heteroepitaxial structure is grown substantially as described in Example I, except that the substrate is Sn-doped n^+ InP, the buffer layer is n^+ Sn-doped (10^{18}cm^{-3}) InP, the layer corresponding to the collector depletion region is 500 nm thick Sn-doped (10^{17}cm^{-3}) InP, the layer corresponding to the base layer is a 20 nm thick Be-doped p^+ ($2 \times 10^{19}\text{cm}^{-3}$) In_{0.53}Ga_{0.47}As layer. This layer is followed by a 150 nm thick Sn-doped n -type ($5 \times 10^{17}\text{cm}^{-3}$) AlAs_{0.44}Sb_{0.56} layer, and this is followed by a 300 nm thick n^+ AlAs_{0.44}Sb_{0.56} layer. After patterning and contacting substantially as in Example I, standard tests show that the heterostructure performs as a HET, with room temperature $\beta > 1000$ for $V_{ce} \geq 1$ volt.

Example III: A unipolar HET is produced substantially as described in Example I, except that the 400 nm thick collector depletion region consists of a su-

perlattice (6 nm thick GaSb layers alternating with 1.5 nm thick $\text{AlSb}_{0.92}\text{As}_{0.08}$ layers), the base layer is 6 nm of InAs, and the emitter layer is 150 nm of $\text{AlSb}_{0.92}\text{As}_{0.08}$. The heterostructure functions as a HET, with room temperature β substantially greater than 10 for $V_{ce} \geq 1$ volt. The presence of the superlattice results in improved transmission of the hot electrons through the base/emitter interface, due to improved velocity matching.

Example IV: A bipolar HET is produced substantially as described in Example II, except that the base layer has composition $\text{In}_{0.55}\text{Ga}_{0.45}\text{As}$. The resulting strained base layer leads to decreased scattering of the hot electrons in the base layer. The heterostructure is found to function as a HET, with room temperature β substantially greater than 10 for $V_{ce} > 1$ volt.

Claims

1. A hot electron transistor comprising:

a) a first region forming an electron emission region (11), a second region (12) forming a base region and a third region (13) forming an electron collection region, said second region being intermediate the first and third regions and forming interfaces and being epitaxial therewith, the first, second and third regions each consisting of compound semiconductor material, the first region material comprising indirect, wide bandgap semiconductor material having an energy minimum in the conduction band at an energy E_i , the second region material being a direct bandgap semiconductor material having an energy minimum in the conduction band at the Γ point in k-space at an energy which is less than E_i , the second region material further differing from the first region material at least at the first/second region interface and having empty electron states at said energy E_i , the first/second region interface being normal to a lattice direction associated with a point in the Brillouin zone, said point corresponding to one of said energy minima in the conduction band of said first material;

b) means (14,15,16) making electrical contact with the first, second and third regions, respectively; and

c) means (11,12,14,15) for injecting hot electrons of average energy E_i from the first into the second region, associated with the hot electrons being a momentum vector k_i having components $k_{i,1}$ and $k_{i,2}$ that are, respectively, perpendicular and parallel to the first/second region interface, and a velocity component normal to the second/third region interface, both energy and parallel momentum compo-

nent $k_{i,2}$ being substantially conserved during injection, wherein the first and second region materials are such that the said empty electron states in the second region material are near to said Γ -minimum and the hot electrons are injected into said empty states, the hot electrons injected into the second region having in said second region a momentum such that the absolute value of $k_{i,2}/k_{i,1}$ is less than 0.2, and wherein the second and third materials are such that said velocity component normal to the second/third region interface undergoes at most 20% change upon crossing of said second/third region interface.

2. The transistor of claim 1, wherein the third region comprises a superlattice, whereby substantial matching of the velocity component normal to the second/third region interface in the part of the third region adjacent to said interface to that in the second region is achieved.

3. The transistor of any of claims 1-2, wherein the first and third region materials are doped materials of a first conductivity type, and the second region material is a doped material of a second conductivity type different from the first conductivity type, and wherein the first, second and third region materials are chosen such that the second region material is strained whereby scattering of the hot electrons in the second region is reduced.

4. The transistor of any of claims 1-3, comprising ambient charge carriers in the second region, wherein the thickness of the second region is less than 50 nm, said ambient charge carriers behaving substantially in the manner of a 2-dimensional charge carrier gas, whereby scattering of the hot electrons in the second region is reduced.

5. The transistor of any of claims 1-4, wherein the first/second region interface is normal to a $\langle 001 \rangle$ lattice direction, associated with the second region material are local X-minima in the conduction band, with an energy being associated with said X-minima, and E_i is selected to be less than said energy associated with said X-minima.

6. The transistor of any of claims 1-5, wherein the first/second region interface is normal to a $\langle 001 \rangle$ lattice direction, and said energy minima associated with the first region material are X-minima.

7. The transistor of claim 1, wherein the first, second, and third regions comprise material of composition $\text{AlSb}_{0.92}\text{As}_{0.08}$, InAs and GaSb, respectively, or of composition $\text{AlAs}_{0.44}\text{Sb}_{0.56}$, $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and InP, respectively.



perlattice (6 nm thick GaSb layers alternating with 1.5 nm thick $\text{AlSb}_{0.92}\text{As}_{0.08}$ layers), the base layer is 6 nm of InAs, and the emitter layer is 150 nm of $\text{AlSb}_{0.92}\text{As}_{0.08}$. The heterostructure functions as a HET, with room temperature β substantially greater than 10 for $V_{ce} \geq 1$ volt. The presence of the superlattice results in improved transmission of the hot electrons through the base/emitter interface, due to improved velocity matching.

Example IV: A bipolar HET is produced substantially as described in Example II, except that the base layer has composition $\text{In}_{0.58}\text{Ga}_{0.42}\text{As}$. The resulting strained base layer leads to decreased scattering of the hot electrons in the base layer. The heterostructure is found to function as a HET, with room temperature β substantially greater than 10 for $V_{ce} > 1$ volt.

Claims

1. A hot electron transistor comprising:

a) a first region forming an electron emission region (11), a second region (12) forming a base region and a third region (13) forming an electron collection region, said second region being intermediate the first and third regions and forming interfaces and being epitaxial therewith, the first, second and third regions each consisting of compound semiconductor material, the first region material comprising indirect, wide bandgap semiconductor material having an energy minimum in the conduction band at an energy E_i , the second region material being a direct bandgap semiconductor material having an energy minimum in the conduction band at the Γ point in k-space at an energy which is less than E_i , the second region material further differing from the first region material at least at the first/second region interface and having empty electron states at said energy E_i , the first/second region interface being normal to a lattice direction associated with a point in the Brillouin zone, said point corresponding to one of said energy minima in the conduction band of said first material;

b) means (14,15,16) making electrical contact with the first, second and third regions, respectively; and

c) means (11,12,14,15) for injecting hot electrons of average energy E_i from the first into the second region, associated with the hot electrons being a momentum vector k_i having components $k_{i,1}$ and $k_{i,2}$ that are, respectively, perpendicular and parallel to the first/second region interface, and a velocity component normal to the second/third region interface, both energy and parallel momentum compo-

nent $k_{i,2}$ being substantially conserved during injection, wherein the first and second region materials are such that the said empty electron states in the second region material are near to said Γ -minimum and the hot electrons are injected into said empty states, the hot electrons injected into the second region having in said second region a momentum such that the absolute value of $k_{i,2}/k_{i,1}$ is less than 0.2, and wherein the second and third materials are such that said velocity component normal to the second/third region interface undergoes at most 20% change upon crossing of said second/third region interface.

2. The transistor of claim 1, wherein the third region comprises a superlattice, whereby substantial matching of the velocity component normal to the second/third region interface in the part of the third region adjacent to said interface to that in the second region is achieved.

3. The transistor of any of claims 1-2, wherein the first and third region materials are doped materials of a first conductivity type, and the second region material is a doped material of a second conductivity type different from the first conductivity type, and wherein the first, second and third region materials are chosen such that the second region material is strained whereby scattering of the hot electrons in the second region is reduced.

4. The transistor of any of claims 1-3, comprising ambient charge carriers in the second region, wherein the thickness of the second region is less than 50 nm, said ambient charge carriers behaving substantially in the manner of a 2-dimensional charge carrier gas, whereby scattering of the hot electrons in the second region is reduced.

5. The transistor of any of claims 1-4, wherein the first/second region interface is normal to a $\langle 001 \rangle$ lattice direction, associated with the second region material are local X-minima in the conduction band, with an energy being associated with said X-minima, and E_i is selected to be less than said energy associated with said X-minima.

6. The transistor of any of claims 1-5, wherein the first/second region interface is normal to a $\langle 001 \rangle$ lattice direction, and said energy minima associated with the first region material are X-minima.

7. The transistor of claim 1, wherein the first, second, and third regions comprise material of composition $\text{AlSb}_{0.92}\text{As}_{0.08}$, InAs and GaSb, respectively, or of composition $\text{AlAs}_{0.44}\text{Sb}_{0.56}$, $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and InP, respectively.



8. The transistor of any of claims 1-7 wherein the transistor has a room temperature current gain $\beta > 10$ at a collector/emitter bias voltage $V_{ce} > 1$ volt.
9. The transistor of claim 4, wherein the second region has a width less than 50 nm, whereby a one dimensional charge carrier gas is produced in the second region.

Patentansprüche

1. Ein Heißelektronentransistor, der umfaßt:
- a) eine eine Elektronenemissionszone (11) bildende erste Zone, eine eine Basiszone bildende zweite Zone (12) und eine eine Elektroneneinsammlungszone bildende dritte Zone (13), wobei besagte zweite Zone zwischen der ersten und dritten Zone liegt und Grenzflächen bildet und epitaxial dazu liegt, die erste, zweite und dritte Zone jeweils aus Verbindungshalbleitermaterial besteht, das Material der ersten Zone Halbleitermaterial mit indirektem großem Bandabstand umfaßt, das ein Energieminimum in dem Leitungsband bei einer Energie E_i aufweist, das Material der zweiten Zone ein Halbleitermaterial mit direktem Bandabstand ist, das ein Energieminimum in dem Leitungsband an dem Γ -Punkt im k-Raum bei einer Energie aufweist, die unter E_i liegt, das Material der zweiten Zone sich weiterhin von dem Material der ersten Zone zumindest an der Grenzfläche zwischen der ersten und zweiten Zone unterscheidet und Elektronenleerzustände bei besagter Energie E_i hat, die Grenzfläche zwischen der ersten und zweiten Zone normal steht zu einer Gitterrichtung, die einem Punkt in der Brillouin-Zone zugeordnet ist, wobei besagter Punkt einem der besagten Energieminima in dem Leitungsband des besagten ersten Materials entspricht;
 - b) Mittel (14, 15, 16), die die ersten, zweiten bzw. dritten Zonen elektrisch kontaktieren; und
 - c) Mittel (11, 12, 14, 15) zum Injizieren heißer Elektronen der mittleren Energie E_i von der ersten in die zweite Zone, wobei den heißen Elektronen zugeordnet sind: ein Impulsvektor k_i mit Komponenten $k_{i,1}$ und $k_{i,2}$, die senkrecht bzw. parallel zu der Grenzfläche zwischen der ersten und zweiten Zone verlaufen, und eine Geschwindigkeitskomponente die normal zu der Grenzfläche zwischen der ersten und zweiten Zone steht, wobei sowohl die Energie als auch die parallele Impulskomponente $k_{i,2}$ während der Injektion im wesentlichen erhalten bleiben, wobei die Materialien der ersten

und zweiten Zone derart beschaffen sind, daß die besagten Elektronenleerzustände in dem Material der zweiten Zone in der Nähe des besagten Γ -Minimums liegen und die heißen Elektronen in besagte Leerzustände injiziert werden, wobei die in die zweite Zone injizierten heißen Elektronen in besagter zweiter Zone einen derartigen Impuls aufweisen daß der Betrag von $k_{i,2}/k_{i,1}$ unter 0,2 liegt, und wobei die zweiten und dritten Materialien derart beschaffen sind, daß die zu der Grenzfläche zwischen der ersten und zweiten Zone normal stehende Geschwindigkeitskomponente sich beim Überqueren der besagten Grenzfläche zwischen der zweiten und dritten Zone höchstens um 20% verändert.

2. Transistor nach Anspruch 1, wobei die dritte Zone ein Übergitter umfaßt, wodurch eine wesentliche Anpassung der zu der Grenzfläche zwischen der zweiten und dritten Zone normalen Geschwindigkeitskomponente an diejenige in der zweiten Zone erzielt wird, in dem Teil der dritten Zone, die der besagten Grenzfläche benachbart ist.
3. Transistor nach einem der Ansprüche 1-2, wobei die Materialien der ersten und dritten Zone dotierte Materialien eines ersten Leitfähigkeitstyps sind, und daß das Material der zweiten Zone ein vom ersten Leitfähigkeitstyp unterschiedlicher zweiter Leitfähigkeitstyp ist, und wobei die Materialien der ersten, zweiten und dritten Zone derart gewählt sind, daß das Material der zweiten Zone verspannt ist, wodurch die Streuung der heißen Elektronen in der zweiten Zone reduziert wird.
4. Transistor nach einem der Ansprüche 1-3, der Umgebungsladungsträger in der zweiten Zone umfaßt, wobei die Stärke der zweiten Zone unter 50 nm liegt, wobei besagte Umgebungsladungsträger sich im wesentlichen wie ein zweidimensionales Ladungsträgergas verhalten, wodurch die Streuung der heißen Elektronen in der zweiten Zone reduziert wird.
5. Transistor nach einem der Ansprüche 1-4, wobei die Grenzfläche zwischen der ersten und zweiten Zone zu einer $\langle 001 \rangle$ Gitterrichtung normal steht, daß lokale X-Minima in dem Leitungsband dem Material der zweiten Zone zugeordnet sind, wobei eine Energie den besagten X-Minima zugeordnet ist, und daß E_i derart ausgewählt ist, daß sie geringer ist, als die besagte Energie, die den besagten X-Minima zugeordnet ist.
6. Transistor nach einem der Ansprüche 1-5, wobei die Grenzfläche zwischen der ersten und zweiten Zone zu einer $\langle 001 \rangle$ Gitterrichtung normal steht,



und daß besagte Energie-Minima, die dem Material der ersten Zone zugeordnet sind, X-Minima sind.

7. Transistor nach Anspruch 1, wobei die ersten, zweiten und dritten Zonen Material der Zusammensetzung $\text{AlSb}_{0,92}\text{As}_{0,08}$, InAs bzw. GaSb oder der Zusammensetzung $\text{AlAs}_{0,44}\text{Sb}_{0,56}$, $\text{In}_{0,53}\text{Ga}_{0,47}\text{As}$ bzw. InP umfassen.
8. Transistor nach einem der Ansprüche 1-7, wobei der Transistor bei Raumtemperatur eine Stromverstärkung $\beta > 10$ bei einer Kollektor/Emitter-Verspannung $V_{ce} > 1$ Volt aufweist.
9. Transistor nach Anspruch 4, wobei die zweite Zone eine Breite von weniger als 50 nm hat, wodurch in der zweiten Zone ein eindimensionales Ladungsträgergas erzeugt wird.

Revendications

1. Transistor à électrons chauds comprenant:
 - a) une première région formant une région d'émission d'électrons (11), une deuxième région (12) formant une région de base et une troisième région (13) formant une région de collecte d'électrons, ladite deuxième régions étant située entre la première et la troisième région, et formant des interfaces et étant épitaxiées avec elles, la première, deuxième et troisième régions étant constituées chacune d'une matière de semiconducteur composé, la matière de la première région comprenant une matière semi-conductrice à large bande interdite indirecte ayant un minimum d'énergie dans la bande de conduction à une énergie E_i , la matière de la deuxième région étant une matière semi-conductrice à bande interdite directe ayant un minimum d'énergie dans la bande de conduction au point Γ dans l'espace des nombres d'ondes à une énergie qui est inférieure à E_i , la matière de la deuxième région étant, en outre, différente de la matière de la première région au moins à l'interface entre la première et la deuxième régions et ayant des états électroniques vides à ladite énergie E_i , l'interface entre la première et la deuxième régions étant normale à une direction de réseau associée à un point dans la zone de Brillouin, ledit point correspondant à un desdits minima d'énergie dans la bande de conduction de ladite première matière;
 - b) des moyens (14, 15, 16) assurant le contact électronique avec la première, la deuxième et la troisième régions respectivement, et
 - c) des moyens (11, 12, 14, 15) pour injecter

des électrons chauds d'énergie moyenne E_i , de la première dans la deuxième région, aux électrons chauds étant associé un vecteur d'ondes k_i ayant des composantes $k_{i,1}$ et $k_{i,2}$ qui sont, respectivement, perpendiculaire et parallèle à l'interface entre la première et la deuxième régions et une régions et une composante de vitesse normale à l'interface entre la deuxième et la troisième régions, l'énergie et la composante de vecteur d'ondes parallèle $k_{i,2}$ étant toutes deux conservées sensiblement pendant l'injection, dans lequel les matières de la première et de la deuxième régions sont telles que lesdits états électroniques vides dans la matière de la deuxième région sont proches dudit minimum Γ et que les électrons chauds sont injectés dans lesdits états vides, les électrons chauds injectés dans la deuxième région ayant dans ladite deuxième région un vecteur d'ondes tel que la valeur absolue de $k_{i,2}/K_{i,1}$ est inférieure à 0,2, et dans lequel les deuxième et troisième matières sont telles que ladite composante de vitesse normale à l'interface de la deuxième et de la troisième régions subit au plus une modification de 20% en traversant l'interface entre la deuxième et la troisième régions.

2. Transistor suivant la revendication 1, dans lequel la troisième région comprend un superréseau, une adaptation sensible de la composante de vitesse normale à l'interface entre la deuxième et la troisième régions dans la partie de la troisième région adjacente à ladite interface étant réalisée avec celle de la deuxième région.
3. Transistor suivant la revendication 1 ou 2, dans lequel les matières de la première et de la troisième régions sont des matières dopées d'un premier type de conductivité, et la matière de la deuxième région est une matière dopée d'un second type de conductivité différent du premier type de conductivité, et dans lequel les matières de la première, de la deuxième et de la troisième régions sont choisies telles que la matière de la deuxième région soit sous contrainte, ce qui réduit la dispersion des électrons chauds dans la deuxième région.
4. Transistor suivant l'une quelconque des revendications 1 à 3, comprenant des porteurs de charge ambiants dans la deuxième région, dans lequel l'épaisseur de la deuxième région est inférieure à 50 nm, lesdits porteurs de charge ambiants se comportant sensiblement à la façon d'un gaz porteur de charge bidimensionnel, ce qui fait que la dispersion des électrons chauds dans la deuxième région est réduite.



5. Transistor suivant l'une quelconque des revendications 1 à 4, dans lequel l'interface entre la première et la deuxième régions est normale à une direction de réseau $\langle 001 \rangle$, des minima X locaux dans la bande de conduction étant associés à la matière de la deuxième région, une énergie étant associée auxdits minima X, et E_i est choisie inférieure à ladite énergie associée audit minima X. 5
6. Transistor suivant l'une quelconque des revendications 1 à 5, dans lequel l'interface entre la première et la deuxième régions est normale à une direction de réseau $\langle 001 \rangle$, et lesdits minima d'énergie associés à la matière de la première région sont des minima X. 10 15
7. Transistor suivant la revendication 1, dans lequel la première, la deuxième et la troisième régions comprennent une matière de composition $\text{AlSb}_{0,82}\text{As}_{0,08}$, InAs et GaSb , respectivement, ou de composition $\text{AlAs}_{0,44}\text{Sb}_{0,56}$, $\text{In}_{0,53}\text{Ga}_{0,47}\text{As}$ et InP , respectivement. 20
8. Transistor suivant l'une quelconque des revendications 1 à 7, dans lequel le transistor a un gain de courant β à température ambiante supérieur à 10 à une tension de polarisation collecteur/émetteur V_{ce} supérieure à 1 volt. 25
9. Transistor suivant la revendication 4, dans lequel la deuxième région a une épaisseur inférieure à 50 nm, ce qui fait qu'un gaz porteur de charge unidimensionnel est produit dans la deuxième région. 30 35 40 45 50 55