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D E C I S I O N
of 30 October 2002

Case Number: T 0858/99 - 3.4.3

Application Number: 95114492.2

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IPC: H01L 29/812

Language of the proceedings: EN

Title of invention:
MES field effect transistor formed in a diamond layer

Applicant:
SUMITOMO ELECTRIC INDUSTRIES, LTD

Opponent:
-

Headword:
Diamond MESFET/SUMITOMO

Relevant legal provisions:
EPC Art. 56

Keyword:
"Inventive step (no)"
"Obvious use of a known different material for its known properties in a prior art device with corresponding modifications in the device parameters"
"Additional objectives of the invention subordinate to that of the primary technical problem addressed by the invention"

Decisions cited:
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Catchword:
-

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Case Number: T 0858/99 - 3.4.3

D E C I S I O N
of the Technical Board of Appeal 3.4.3
of 30 October 2002

Appellant: SUMITOMO ELECTRIC INDUSTRIES, LTD
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Decision under appeal: **Decision of the Examining Division of the European Patent Office posted 31 March 1999 refusing European patent application No. 95 114 492.2 pursuant to Article 97(1) EPC.**

Composition of the Board:

Chairman: R. K. Shukla
Members: G. L. Eliasson
J. H. Van Moer

Summary of Facts and Submissions

I. European patent application No. 95 114 492.2 was refused in a decision of the examining division dated 31 March 1999. The ground for the refusal was that the claim 1 according to the main request and first and second auxiliary requests was not clear, contrary to the requirements of Article 84 EPC. Also, the subject matter of claim 1 according to all the above requests, in so far it could be understood, did not involve an inventive step having regard to the prior art documents:

D1: GB-A-2 254 733;

D2: EP-A-0 457 508;

D5: Applied Physics Letters, No. 57, vol. 13, 1990, pages 1316 to 1317; and

D6: IEEE Transactions on Electron Devices, vol. ED-28, No. 5, May 1981, pages 505 to 510.

II. The appellant (applicant) lodged an appeal on 9 June 1999 paying the appeal fee the same day. A statement of the grounds of appeal was filed on 6 August 1999 together with new claims.

III. In response to a communication of the Board accompanying summons to oral proceedings, the appellant filed with the letter dated 30 September 2002 claims 1 to 9 according to a main request, claims 1 to 9 according to a first auxiliary request, claims 1 to 8 according to second auxiliary request, and claims 1 to 3 according to a third auxiliary request.

IV. At the oral proceedings held on 30 October 2002, the appellant requested that the decision under appeal be set aside and a patent be granted on the basis of any of the requests filed with the letter of 30 September 2002.

V. Independent claims 1 and 5 according to the main request read as follows:

"1. A field effect transistor comprising:

a buffer layer (30) made of a non-intentionally doped highly resistant diamond formed on a substrate (20);

an active layer (40) which is made of a conductive diamond on said buffer layer (30), wherein the active layer (40) is doped with boron, the dopant concentration in said active layer (40) being within the range of 5 x 10^3 ppm to 10^5 ppm such that conduction of carriers is metallically dominated thereby, and wherein the active layer (40) has a thickness of about 7 nm such that dopant distribution is two-dimensionally aligned thereby;

a cap layer (31) made of a non-intentionally doped highly resistant diamond on said active layer (40);

a gate electrode layer (50) formed on said cap layer (31) so as to make Schottky contact therewith;

a source electrode layer (51) which makes ohmic contact with a laminate structure of said buffer, active and cap layers (30, 31, 40); and

a drain electrode layer (52) which makes ohmic contact with the laminate structure of said buffer, active and cap layers (30, 31, 40)."

"5. A method of making a field effect transistor, comprising the steps of:

a first step in which a buffer layer (30) made of a non-intentionally doped highly resistant diamond, and an active layer (40) made of a conductive diamond and doped with boron, and a cap layer (31) made of a non-intentionally doped high resistant diamond are formed by being successively mounted on a substrate (20), wherein the dopant concentration is within the range of 5×10^3 ppm to 10^5 ppm such that conduction of carriers is metallically dominated thereby, wherein said active layer (40) has a thickness of about 7 nm such that dopant distribution is two-dimensionally aligned thereby; and

a second step in which a gate electrode layer (50) formed on said cap layer (31) so as to make Schottky contact therewith and each of a source electrode layer (51) and a drain electrode layer (52) which make ohmic contact with a laminate structure of said buffer, active and cap layers (30, 31, 40)."

VI. Claim 1 according to the first auxiliary request differs from claim 1 of the main request in that the buffer layer (30) and the cap layer (31) are specified to be made of "a **non-doped, at least** non-intentionally doped highly resistant diamond" (emphasis added by the Board). Claim 5 according to the first auxiliary request is identical to that of the main request.

VII. Claim 1 according to the second auxiliary request corresponds to claim 1 according to the first auxiliary request with the following text added at the end:

"wherein two high-concentration dope (sic) regions are formed in said cap layer (31), said two high-concentration dope (sic) regions have dopant concentrations higher than that of the other region in said cap layer (31), and said source and drain electrode layers (51, 52) are formed on the two high-concentration dope (sic) regions in said cap layer (31), respectively."

Claim 4 according to the second auxiliary request differs from claim 5 according to the main request in that the above text is added at the end of claim 4.

VIII. Claim 1 according to the third auxiliary request relates to a method and differs from claim 5 according to the main request in that the following text is added at the end of claim 1:

"wherein, in said first step, a high-pressure synthesis technique is used to form said buffer layer (30), active layer (40), and cap layer (31)."

IX. The reasons given in the decision under appeal with regard to inventive step, in so far as being relevant to the present decision, can be summarized as follows:

(a) Document D5 discloses a pulse-doped GaAs structure to be used in a FET where a 10 nm thin active layer is formed between by an unintentionally doped buffer and an unintentionally doped cap layer.

(b) The problem to be solved relates to transferring the GaAs-technology to diamond. The methods of forming doped and undoped diamond layers, as well as the formation of ohmic and Schottky contacts on diamond layers are known from document D2.

Document D6 gives a clear indication to increase the doping density of the active layer achieving a degenerate doping density, i.e. a metallically dominated conduction.

X. The appellant presented essentially the following arguments in support of inventive step:

(a) The claimed device differs from that of document D5 not only in that GaAs is substituted with diamond, but in several other respects, as discussed in detail below. Thus, the large number of modified features required to produce a functioning diamond MESFET indicates that the transfer from GaAs-technology to diamond was not straight-forward, contrary to the view held in the decision under appeal.

(b) In addition to addressing the problem of transferring the known MESFET structure in GaAs-technology to diamond, the present application also has the further objectives: The high resistance of undoped diamond makes it possible to reduce the gate leakage with respect to a device made of GaAs (cf. application as published, page 3, lines 28 to 29). The claimed device also provides a reduced thickness of the doped active layer, thereby reducing the scattering of carriers further (cf. application, page 3, lines 22 to 27).

(c) Since silicon is known to be an n-type dopant for diamond as well as for GaAs, the skilled person would use silicon as a dopant in the device of document D5. Therefore, the skilled person would have no incentive for using the p-type dopant boron, as in the present invention.

(d) There is no suggestion in the prior art to increase the doping concentration in the active layer from a value of 80 ppm as employed in document D5 to an extremely high concentration value lying in the range of 5×10^3 ppm to 10^5 ppm as claimed in the application in suit. In particular, document D6 does not teach to use carrier concentrations beyond that of document D5. Therefore, document D6 is not useful for giving the skilled person the necessary hint to arrive at the extremely high concentration range according to the present invention.

(e) In document D5, the GaAs buffer and cap layers are made p- and n-type, respectively, by controlling the V/III ratio during growth and cannot therefore be considered as "non-intentionally doped", contrary to the claimed device. A skilled person faced with the task of transferring the teaching of document D5 to diamond technology would thus learn from document D5 that the buffer and cap layers have to be of p- and n-type. Since diamond is an elemental semiconductor, the skilled person would have no choice than to *intentionally* dope the diamond to arrive at the p-n^+-n structure suggested in document D5.

Reasons for the Decision

1. The appeal complies with Articles 106 to 108 and Rule 64 EPC and is therefore admissible.

2. *Inventive step - main request*

The only issue in the present appeal is that of inventive step having regard to the prior art documents D2, D5, and D6.

2.1 Document D5 which is the closest prior art discloses a GaAs i-n^+-i structure used in a MESFET. The i-n^+-i structure is grown using metal-organic vapor phase epitaxy (MOVPE) and comprises a thin active layer (10 nm) doped with Si donor dopants at a concentration of 4.0 x 10^{18} cm^{-3} sandwiched between an undoped buffer layer and an undoped cap layer (cf. page 1316, paragraph bridging right and left hand columns). The buffer and cap layers are referred to as "undoped" but are of p- and n-conductivity type, respectively, through control of the Ga/As ratio during growth. The ionized Si donors in the active layer give rise to a two-dimensional electron gas confined in the active layer and having an electron density of 5.1 x 10^{12} electrons cm^{-2}. The Fermi level E_F in the active layer is reported to lie above the conduction band edge E_C (cf. Figure 2; paragraph bridging pages 1316 and 1317). The structure is shown to have high electron mobility with weak temperature dependence (cf. Figure 3 with accompanying text).

Since document D5 relates to a structure which is used in a MESFET, and a MESFET includes a Schottky gate electrode and ohmic source and drain electrodes, these features are implicit in document D5.

2.2 Document D6 discloses theoretical calculations for a GaAs planar doped FET structure, i.e. the same structure as in document D5 but where the active layer consists of only a single atomic plane (cf. Figure 1 with accompanying text). It is taught in document D6 that for high doping concentrations, such as 3.5×10^{12} cm^{-2} (cf. Figure 4 with accompanying text; page 510, "Conclusions"), the transfer characteristics are linear, whereas for low doping concentrations, such as 2.3×10^{10} cm^{-2}, the transfer characteristics are exponential. It is furthermore stated that if the doping density exceeds 2×10^{12} cm^{-2}, then the electron density is degenerate near the active layer (cf. page 507, left column, second paragraph). A degenerate electron density is also observed for the example having a doping density of 3.5×10^{12} cm^{-2} (cf. Figure 4a where the potential crosses the degenerate limit).

2.3 Document D2 discloses a diamond FET having a p-doped active layer 2 formed on a diamond substrate 1. An undoped diamond layer 3 is formed on the active layer. The dopant concentration in the active layer is preferably more than 10^{20} cm^{-3} which makes the layer degenerate (page 5, lines 37 to 39). The carriers diffuse from the active layer to the undoped layer 3 which acts as the channel. Source and drain electrodes are formed on the undoped layer 3. The diamond layers are formed using microwave plasma CVD.

2.4 In the device of claim 1, the active layer is specified to have a dopant concentration such that "conduction of carriers is *metallically dominated* thereby". According to the description, this means that the Fermi level of the active layer approaches a valence band or a conduction band (cf. the application as published, page 4, lines 58 to 59). In device of document D5, the Fermi energy E_F in the active layer lies above the conduction band edge E_C (cf. Figure 2). The term

"degenerate electron density" is used in document D6 which is the generally accepted term in the art for the case when the Fermi level approaches a conduction band, i.e. it has the same meaning as the term "metallically dominated conduction" used in the application in suit. In Figures 3 and 4 of document D6, the electron density around the active layer is above the degenerate limit, and thus in this region, the conduction is metallically dominated.

Therefore, the prior art document D5 discloses a device having an active layer with a dopant concentration such that the carrier conduction is "metallically dominated" within the meaning used in the application in suit. This has not been disputed by the appellant.

2.5 The device of claim 1 differs from that of document D5 in that

(i) diamond is used instead of GaAs;

(ii) boron is used instead of silicon as a dopant;

(iii) the active layer has a doping concentration of 5×10^3 to 10^5 ppm boron, whereas in document D5, the active layer is about 10 nm thick and is doped with Si at a concentration of 4.0×10^{18} cm^{-3}, which corresponds to a doping concentration of 80 ppm;

(iv) the active layer has a thickness of 7 nm instead of 10 nm as disclosed in document D5; and

(v) the buffer and cap layers are not intentionally doped; whereas in document D5, they are not doped but are nevertheless p- and n-type, respectively, through control of the Ga/As ratio during growth.

2.6 It follows from the application in suit that the objective technical problem addressed by the application in suit relates to providing a pulse-doped transistor which can be used for high temperature applications (cf. the application in suit, page 6, line 52 to page 7, line 12).

2.6.1 The appellant argued that the application in suit also has additional objectives, such as decreasing the gate-leakage current and minimizing the thickness of the active layer (cf. item X(b) above). The Board is however of the opinion that the change of material from GaAs in the device of document D5 requires a review of all device parameters in order to accommodate for the differences in material properties, and therefore, the additional objectives stated by the appellant also fall within the above formulated technical problem.

Furthermore, the Board also finds that the additional objectives recited by the appellant must be considered to be subordinate to that of the technical problem of providing a transistor for high-temperature applications, since the objectives of decreasing the gate-leakage current and minimizing the thickness of the active layer are to be considered in the context of devices which are suitable for high-temperature applications.

2.7 Regarding difference (i), the Board agrees with the opinion of the examining division that there was a clear incentive for the skilled person at the priority date of the application in suit to try such transfer of technology known from GaAs to diamond, as diamond was well-known in the art to posses properties such as high thermal conductivity and large bandgap which makes diamond particularly suitable for applications requiring high operating temperatures. Moreover, as acknowledged in the application in suit (cf. page 2,

lines 22 to 30), it has been known to employ diamond in semiconductor devices as semiconductor material, so that the advantages of diamond for high-temperature applications were already known in the art. The appellant has also not provided any arguments to the contrary of this view.

2.8 As to the dopant in the active layer (difference (ii) above), boron was the only known dopant for diamond at the priority date of the application in suit which provided a reasonable number of dopant atoms which could be activated to release charged carriers.

Although the appellant correctly observed that n-type dopants for diamond, such as silicon and nitrogen, were known from e.g. document D1 (cf. item X(c) above), it was known to be extremely difficult to produce high-quality n-type diamond, and therefore practically only boron-doped p-type diamond was used for electronic devices. In document D1, silicon is admittedly mentioned as an n-type dopant for diamond (cf. page 1, second paragraph), but boron is the only dopant actually used in the embodiments of document D1. Therefore, the Board is of the opinion that there was no viable alternative to boron at the priority date of the application in suit.

2.9 The doping concentration is expressed in parts per million (ppm) in the application in suit, i.e. in terms of the proportion of dopant atoms to carbon atoms. The prior art documents D2 and D5, on the other hand, disclose the doping concentrations in terms of dopant atoms/cm^3 which is the customary unit in the field of semiconductor devices. In order to be able to compare the claimed range of 5×10^3 ppm to 10^5 ppm for the dopant concentration with the values disclosed in the prior art, the appellant provided the examining division with an appropriate conversion factor (cf.

letter dated 9 December 1997). It follows from this information that the claimed end values 5 x 10^3 ppm and 10^5 ppm correspond to 1 x 10^{21} cm^{-3} and 2 x 10^{22} cm^{-3}, respectively.

Document D6, which is a theoretical article, only discloses a planar doping density in terms of atoms/cm^{-2}, i.e. the planar doping density which roughly corresponds to the doping concentration expressed as atoms/cm^3 times the thickness of the active layer.

In this respect, the appellant argued that the claimed range of 5 x 10^3 ppm to 10^5 ppm for the dopant concentration (difference (iii) above) is much higher than the value of 4.0 x 10^{18} cm^{-3} disclosed in document D5 which corresponds to only 80 ppm (cf. item X(d) above).

2.9.1 Although the appellant correctly observes that a doping concentration of 20 ppm boron in diamond as derived from document D5 is too low for producing the desired linear transfer characteristic and temperature stable device characteristics, the Board finds nevertheless that the skilled person would consider much higher dopant concentrations, since both the prior art documents D5 and D6 teach that these desired device properties can only be attained when the carrier concentration is sufficiently high. Document D5 discloses a Fermi level E_F lying above the conduction band edge E_C in the n-doped active layer, i.e. the semiconductor in the active layer which has a metallically dominated conduction (cf. Figure 2 with accompanying text, as well as item 2.3 above). Document D6 describes in detail that the linear

transfer characteristics are only attained when the carrier concentration is sufficiently high for forming a degenerate semiconductor in and around the active layer, i.e. an active layer having a metallically dominated conduction (cf. item 2.3 above).

Considering that the dopant concentrations considered in document D6 reach across two orders of magnitude (Figures 2 to 4), and that document D6 gives a clear teaching that linear transfer characteristics are only possible for sufficiently high dopant concentrations, the skilled person would in his pursuit of a diamond device having linear transfer characteristics consider increasing the doping concentration with one or several orders of magnitude compared to that disclosed in document D5 for GaAs.

2.9.2 A large increase of the doping concentration would also be considered when taking into account the well-known fact that, in contrast to silicon in GaAs, only a small proportion of boron atoms in diamond are "activated" to release carriers in the semiconductor. Therefore, in order to obtain a desired concentration of holes in diamond, a correspondingly higher number of boron atoms have to be introduced.

2.9.3 The Board also notes that it was known from document D2 that boron could be doped at very high concentration values as claimed, so that it was known to be technically feasible to produce diamond with very high dopant concentrations. The boron concentrations in diamond disclosed in document D2 range from 10^{18} cm^{-3} to 10^{22} cm^{-3}, i.e. from 5 ppm to 5 x 10^4 ppm (cf. D2, page 5, lines 28 to 32; claim 2).

2.10 Regarding the thickness of the active layer (difference (iv) above), the Board agrees with the view held in the decision under appeal that the thickness of 10 nm disclosed in document D5 is considered to be sufficiently close to the claimed value of 7 nm that the slight difference falls within that reached through routine optimization procedure. It is also taught in documents D5 and D6 that the thickness of the active layer should be as thin as practically possible, ideally only a single atom layer, in order to reduce the adverse effects of the ionized dopants (cf. D5, page 1316, first paragraph; D6, page 505, "Introduction").

2.11 As to feature (v) above, the examining division did not consider the "non-intentionally doped" buffer and cap layers to differ from those of the device of document D5, since the p-type buffer layer and the n-type cap layer in the device of document D5 were produced without introducing dopants. In the light of the appellant's argument's (see also the wording of claim 1 according to the first auxiliary request), however, the term "non-intentionally doped" in claim 1 should be construed as meaning "intrinsic diamond".

Since the buffer and cap layers in the device of document D5 are of p- and n-conductivity type, respectively, through control of the Ga/As ratio without introducing dopants, the appellant argued that the skilled person following the teaching of document D5 to diamond would have no choice than to dope the buffer layer and the cap layer, which is contrary to the teaching of the present invention (cf. item X(e) above).

2.11.1 The above argument is not convincing, since the introduction of dopants in the buffer and cap layers would run contrary to the teachings of both documents D5 and D6. In document D5, the structure is described as i-n^+-i, and the importance of having *all* the dopant atoms localized to a thin active layer is emphasized (cf. D5, page 1316, left column, first paragraph). Similarly, document D6 discloses a structure having undoped buffer layer and cap layer and where all the dopants are localized to the active layer (cf. Figure 1 with accompanying text). Furthermore, the technique of growing non-stoichiometric, undoped GaAs films with MOVPE was known in the art for neutralizing (compensating) impurities present in GaAs films grown using MOVPE. The skilled person taking the above facts into account would therefore consider the measure of controlling the conductivity types of the undoped buffer and cap layers through the Ga/As ratio, as disclosed in document D5, to be relevant only for growth of III-V compound semiconductors using MOVPE.

2.12 Finally, as to the argument of the appellant that the combination of the many differing features would render the claimed device inventive (cf. item X(a) above), the Board finds that all the differences (ii) to (v) above are direct consequences of the replacement of GaAs with diamond, since the different material properties between GaAs and diamond require corresponding modifications of the device parameters in order to ensure proper functioning of the MESFET device. The Board is also not able to find any new effect arising from the combination of the features (ii) to (v), and as discussed above, nor did any of the features (ii) to (v) have to be modified in an unexpected manner.

2.13 Therefore, in the Board's judgement, the subject matter of claim 1 does not involve an inventive step within meaning of Article 56 EPC.

The same reasoning applies *mutatis mutandis* for the subject matter of independent claim 5 as well.

3. *Inventive step - First auxiliary request*

Claim 1 according to the first auxiliary request only differs from that of the main request in that the buffer and cap layers are specified to be "non-doped, at least non-intentionally doped". The features are however already taken into consideration in the reasoning above so that the subject matter of claim 1 according to the first auxiliary request does not involve an inventive step for the same reasons as given for the main request.

4. *Inventive step - Second auxiliary request*

4.1 The device of claim 1 according to the second auxiliary request differs from that of document D5, in addition to the features (i) to (v) referred to above, in that

> two high-concentration doped regions are formed in the cap layer and the source and drain layers are formed on the two doped regions, respectively; whereas document D5 does not explicitly disclose the source/drain contact structure.

4.2 In a MESFET, such as the device of document D5, the source and drain electrodes have to form ohmic contacts with the semiconductor. In order to form such ohmic contacts, highly doped source/drain regions are formed in the semiconductor where the metal source/drain electrodes are to be formed, and/or the metal source/drain electrodes are allowed to form an alloy

with the semiconductor. In any case, the result is that highly doped semiconductor regions are formed directly below the metal source/drain electrodes. Such highly doped regions in the cap layer below the source/drain electrodes are also mentioned in document D6 (cf. page 506, right hand column, second paragraph). Therefore, the inclusion of the above feature is necessary for obtaining a properly functioning MESFET device and thus cannot be considered as involving an inventive step within the meaning of Article 56 EPC.

5. *Inventive step - Third auxiliary request*

The method of claim 1 according to the third auxiliary request differs from that of document D5, in addition to the features (i) to (v) referred to above, in that

> a high-pressure synthesis technique is used to form the buffer layer, active layer, and cap layer, whereas in the method of document D5, a metal-organic vapor phase deposition technique is used.

Document D2, which relates to the formation of diamond semiconductor devices, discloses the use of microwave plasma CVD technique for forming the diamond layers (cf. e.g. page 6, line 16 to page 7, line 14). In the light of the very limited number of deposition techniques available for forming epitaxial layers of diamond, however, the Board cannot see any inventive merit in choosing a high-pressure synthesis technique for this purpose. The application in suit furthermore does not indicate any particular technical problem addressed by the use of high-pressure synthesis over other techniques. In fact, all the embodiments of the application in suit exclusively use the same microwave plasma CVD technique as known from document D2.

Therefore, in the Board's judgement, the subject matter of claim 1 according to the third auxiliary request does not involve an inventive step within the meaning of Article 56 EPC.

Order

For these reasons it is decided that:

The appeal is dismissed.

The Registrar: The Chairman:

P. Martorana R. K. Shukla