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(54) **GRAPHENE-BASED PLASMONIC NANO-TRANSCEIVER EMPLOYING HEMT FOR TERAHERTZ BAND COMMUNICATION**

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H04B 10/90 (2013.01)
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CPC ***H04B 10/90*** (2013.01); ***H01L 29/1606*** (2013.01); ***H01L 29/2003*** (2013.01); ***H01L 29/7787*** (2013.01)

(58) **Field of Classification Search**
CPC H01L 29/2003; H01L 29/201; H01L 29/7787; H01L 29/205
USPC 257/76, 194, E29.246
See application file for complete search history.

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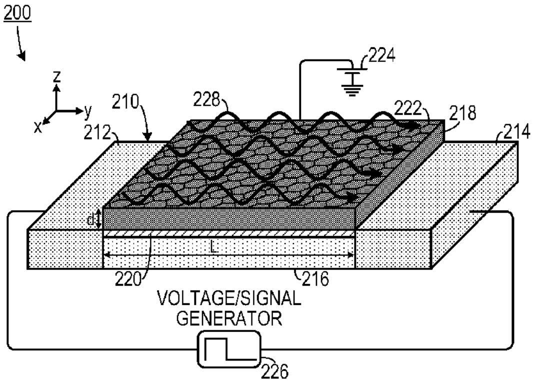
(57) **ABSTRACT**

A communication element includes a high electron mobility transistor including a gate layer. A graphene layer is disposed on the gate layer. A communication system includes a signal source, a plasmonic transmitter, a first plasmonic antenna, a second plasmonic antenna, a plasmonic receiver and a signal detector. The signal source generates a transmitted signal. The plasmonic transmitter generates a first surface plasmonic polariton wave signal corresponding to the transmitted signal. The first plasmonic antenna generates an electromagnetic signal corresponding to the surface plasmon polariton wave signal. The second plasmonic antenna generates a second surface plasmon polariton wave signal corresponding to the electromagnetic signal. The plasmonic receiver generates a received signal corresponding to the second surface plasmon polariton wave signal. The signal detector detects the received signal.

25 Claims, 4 Drawing Sheets



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H01L 29/20	(2006.01)
H01L 29/778	(2006.01)
H01L 29/16	(2006.01)

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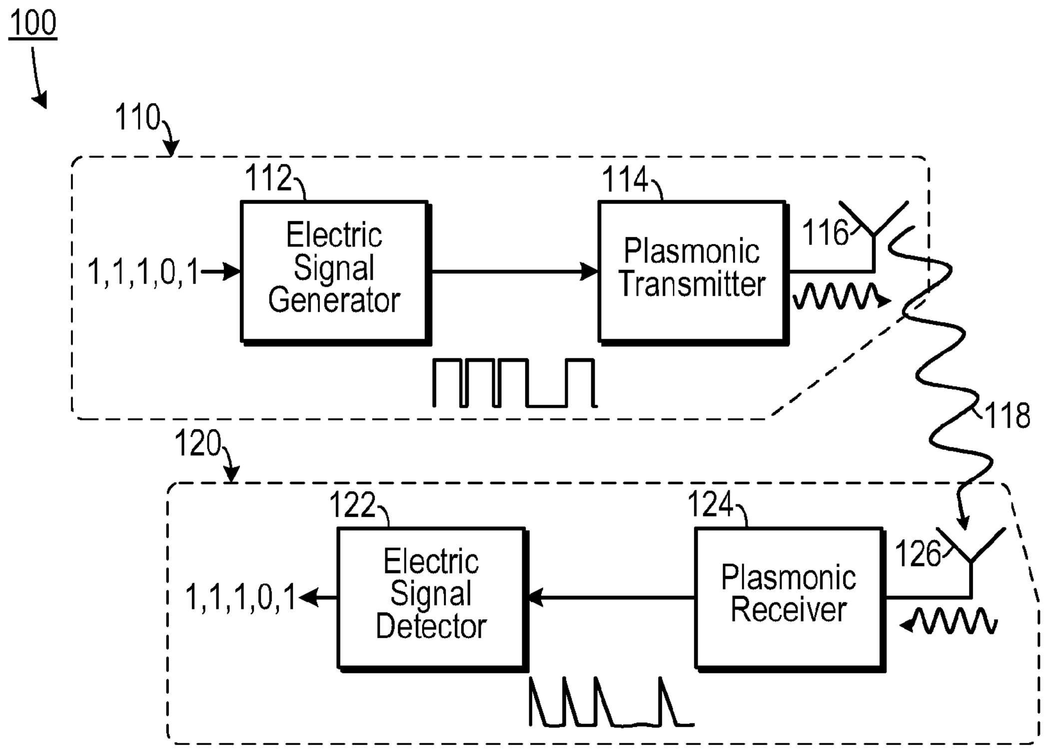
100
110
112
Electric Signal Generator
114
Plasmonic Transmitter
116
1,1,1,0,1
118
120
122
Electric Signal Detector
124
Plasmonic Receiver
126
1,1,1,0,1

FIG. 1

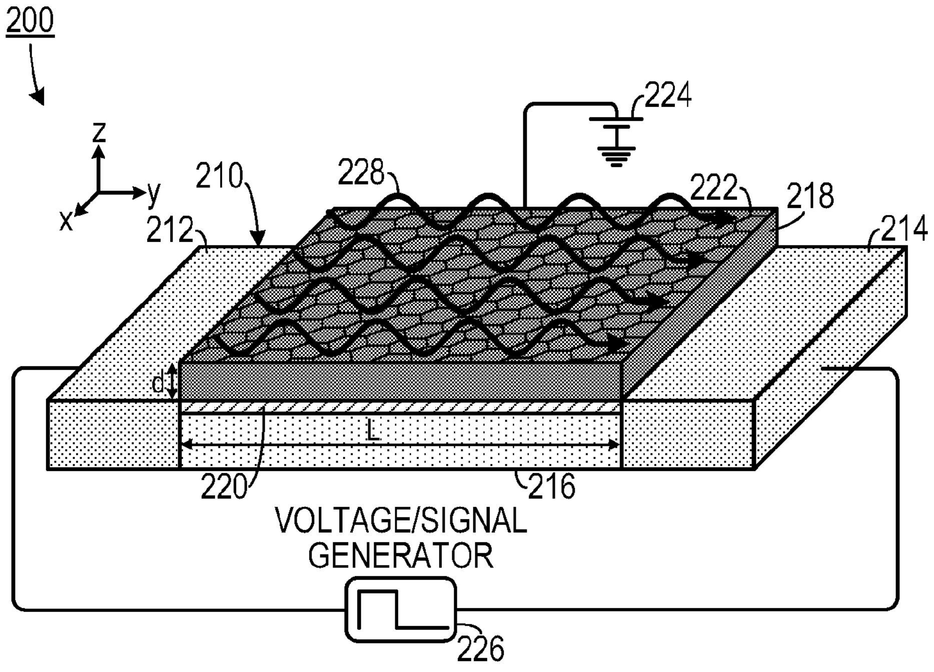
200
z
y
x
210
212
228
224
222
218
214
d
L
220
216
VOLTAGE/SIGNAL
GENERATOR
226

FIG. 2A

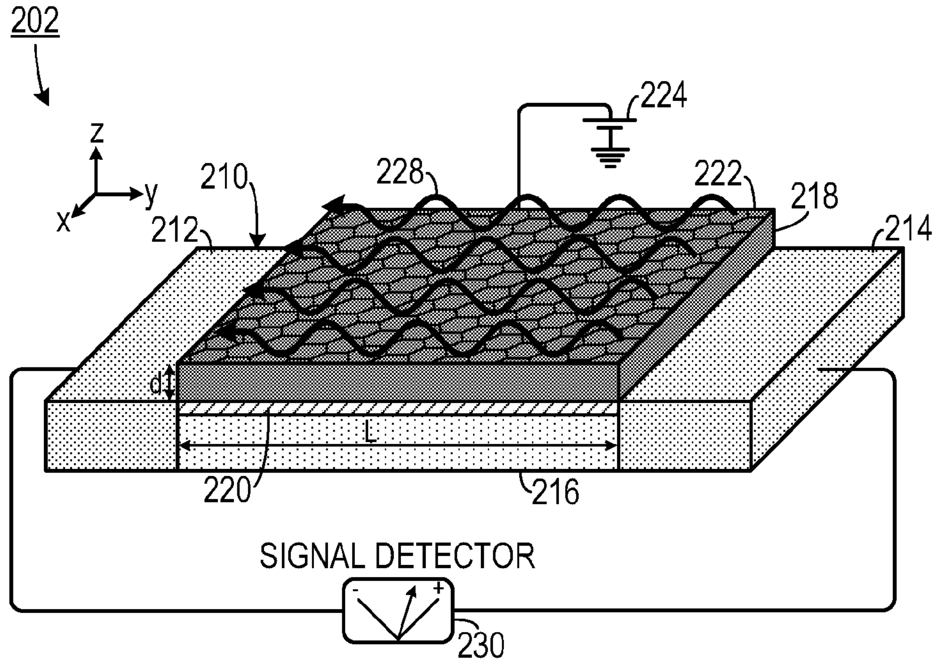
202
z
y
x
210
212
228
224
222
218
214
d
L
220
216
SIGNAL DETECTOR
-
+
230

FIG. 2B

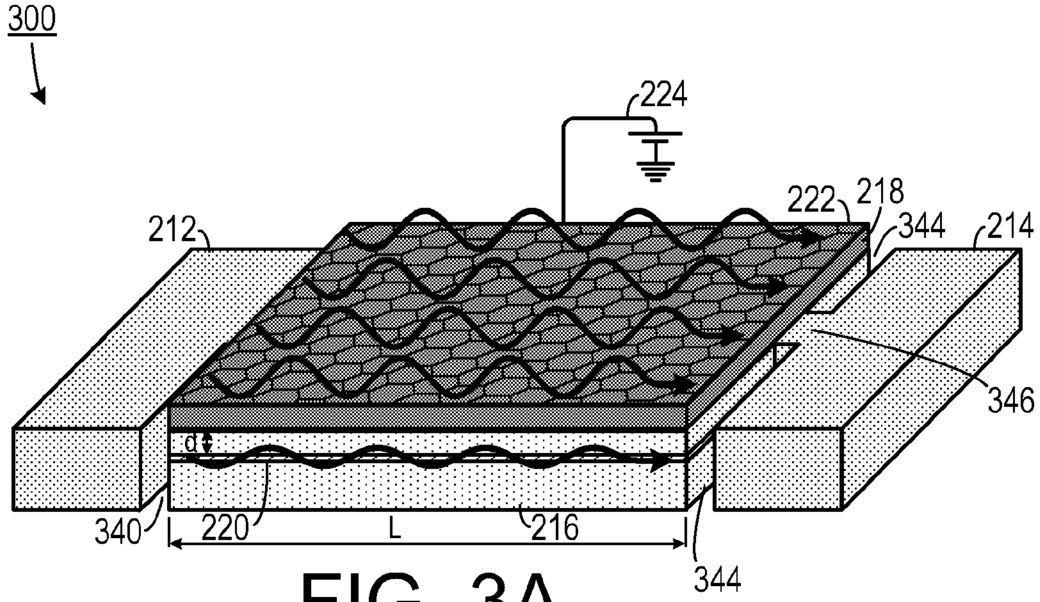
300
224
222
218
344
214
212
346
d
340
220
L
216
344

FIG. 3A

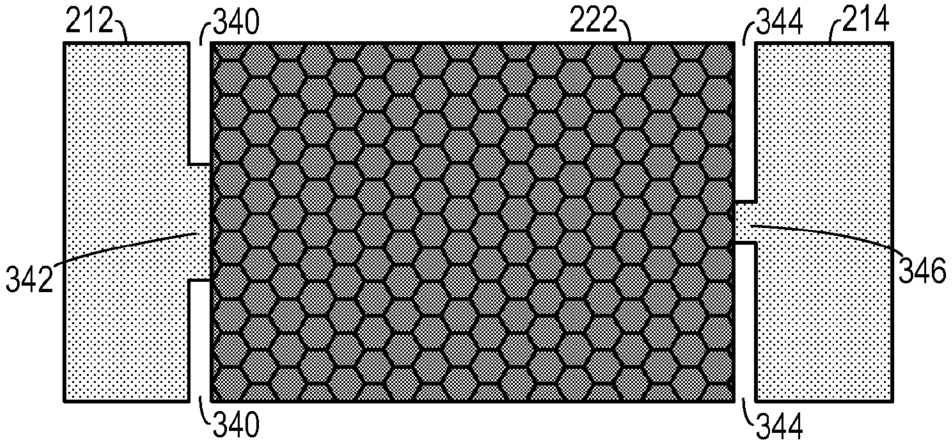
212
340
222
344
214
342
346
340
344

FIG. 3B

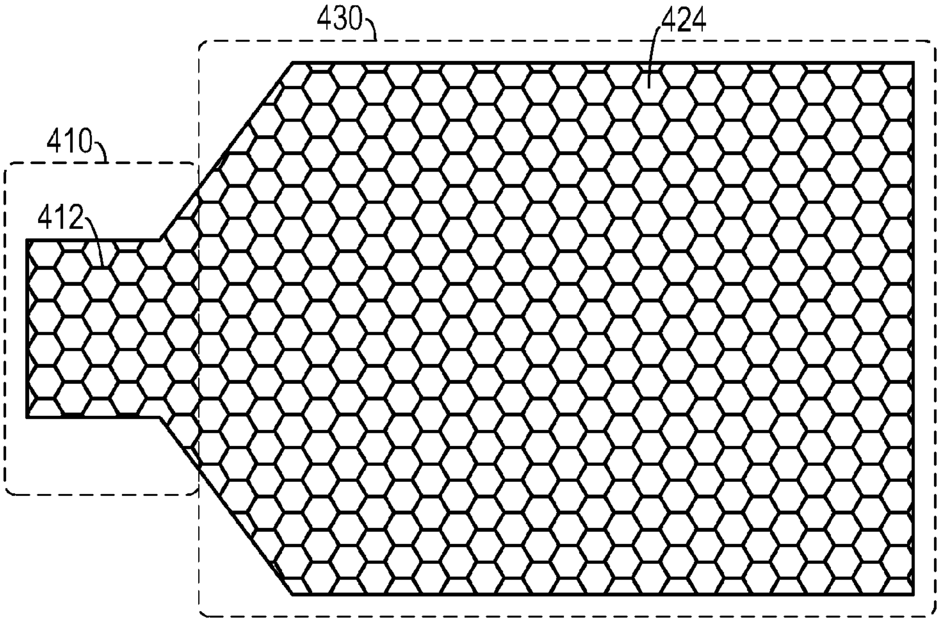

FIG. 4A

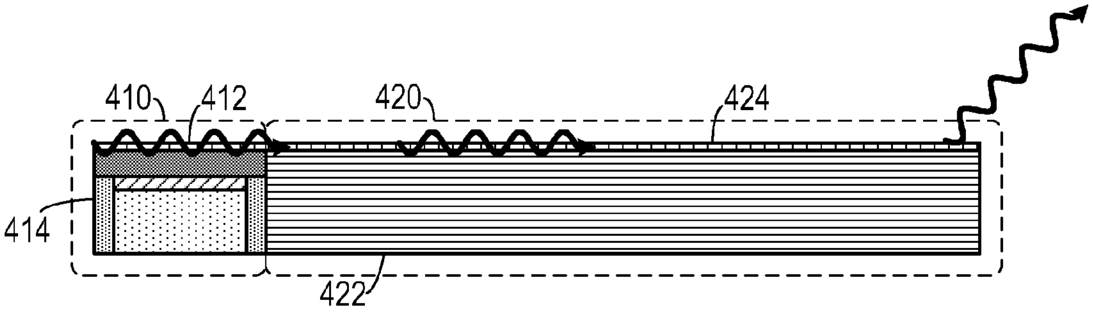

FIG. 4B

GRAPHENE-BASED PLASMONIC NANO-TRANSCEIVER EMPLOYING HEMT FOR TERAHERTZ BAND COMMUNICATION

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 61/912,943, filed Dec. 6, 2013, and 61/952,926, filed Mar. 14, 2014, the entirety of each of which is hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to communications devices and, more specifically, to a plasmonic communications device.

2. Description of the Related Art

Wireless data traffic has drastically increased due to a change in the way information is created, shared and consumed. This change has been accompanied by an increasing demand for much higher speed wireless communication systems. In particular, wireless data rates have doubled about every eighteen months over the last three decades and they are quickly approaching the capacity of wired communication systems. Following this trend, wireless terabit-per-second (Tbps) data links will be needed within the next five to ten years. Advanced physical layer solutions and, more importantly, new spectral bands will be required to support these extremely high data rates.

In this context, terahertz (THz) band communication is envisioned as a key wireless technology to satisfy this demand by alleviating the spectrum scarcity and capacity limitations of current wireless systems, and enabling many applications in diverse fields. The THz band is the spectral band that spans the frequencies between 0.1 THz and 10 THz.

Wireless technologies below 0.1 THz are generally not able to support Tbps links. On the one hand, advanced digital modulations, e.g., Orthogonal Frequency Division Multiplexing (OFDM), and sophisticated communication schemes, e.g., very large scale Multiple Input Mul-tiple Output (MIMO) systems, are being used to achieve a very high spectral efficiency at frequencies below 5 GHz. However, the scarcity of the available bandwidth limits the achievable data rates. For example, in Long-Term Evolution Advanced (LTEA) networks, peak data rates in the order of 1 Gbps are possible when using a four-by-four MIMO scheme over a 100 MHz aggregated bandwidth. These data rates are three orders of magnitude below the targeted 1 Tbps. On the other hand, millimeter wave (mm-wave) communication systems, such as those at 60 GHz, can support data rates in the order of 10 Gbps within one meter. This data rate is still two orders of magnitude below the expected demand. The path to improve the data rate involves the development of more complex transceiver architectures able to implement physical layer solutions with much higher spectral efficiency. However, the usable bandwidth is usually limited to less than 7 GHz, which effectively imposes an upper bound on the data rates.

Therefore, there is a need for a communications system that can support THz band communications.

SUMMARY OF THE INVENTION

The disadvantages of the prior art are overcome by the present invention which, in one aspect, is a communication element that includes a high electron mobility transistor including a gate layer. A graphene layer is disposed on the gate layer.

In another aspect, the invention is a communication system that includes a signal source, a plasmonic transmitter, a first plasmonic antenna, a second plasmonic antenna, a plasmonic receiver and a signal detector. The signal source is configured to generate a transmitted signal. The plasmonic transmitter is responsive to the transmitted signal and is configured to generate a first surface plasmonic polariton wave signal corresponding to the transmitted signal. The first plasmonic antenna is responsive to the first surface plasmonic polariton wave signal and is configured to generate an electromagnetic signal corresponding to the surface plasmon polariton wave signal. The second plasmonic antenna is responsive to the electromagnetic signal and is configured to generate a second surface plasmon polariton wave signal corresponding to the electromagnetic signal. The plasmonic receiver is responsive to the second surface plasmon polariton wave signal and is configured to generate a received signal corresponding to the second surface plasmon polariton wave signal. The signal detector is configured to detect the received signal.

These and other aspects of the invention will become apparent from the following description of the preferred embodiments taken in conjunction with the following drawings. As would be obvious to one skilled in the art, many variations and modifications of the invention may be effected without departing from the spirit and scope of the novel concepts of the disclosure.

BRIEF DESCRIPTION OF THE FIGURES OF THE DRAWINGS

FIG. **1** is a block diagram of a communication system.

FIG. **2**A is a top front view of a first embodiment of a plasmonic communication element configured as transmitter.

FIG. **2**B is a top front view of a first embodiment of a plasmonic communication element configured as a receiver.

FIG. **3**A is a top front view of a second embodiment of a plasmonic communication element

FIG. **3**B is a top plan view of the embodiment shown in FIG. **4**A.

FIG. **4**A is a top plan view of ab embodiment of a plasmonic communication element coupled to a plasmonic antenna.

FIG. **4**B is a side elevational view of the embodiment shown in FIG. **5**A.

DETAILED DESCRIPTION OF THE INVENTION

A preferred embodiment of the invention is now described in detail. Referring to the drawings, like numbers indicate like parts throughout the views. Unless otherwise specifically indicated in the disclosure that follows, the drawings are not necessarily drawn to scale. As used in the description herein and throughout the claims, the following terms take the meanings explicitly associated herein, unless the context clearly dictates otherwise: the meaning of "a," "an," and "the" includes plural reference, the meaning of "in" includes "in" and "on." U.S. patent application Ser. No. 14/253,539, filed on Apr. 15, 2014, discloses plasmonic nano-antennas and is incorporated herein by reference for the purpose of disclosing the same.

As shown in FIG. **1**, one embodiment of a THz band plasmonic-based communications system includes a transmitting unit **110** that transmits a THz band electromagnetic signal **118** to a receiving unit **120**. The transmitting unit **110** typically includes a signal generator **112** that generates an electric signal. A plasmonic transmitter **114** generates a surface plasmonic polariton (SPP) signal, which corresponds to the electric signal, that is converted to the electromagnetic signal **118** by a first plasmonic nano-antenna **116**. The electromagnetic signal **118** is received by a second plasmonic nano-antenna **126**, which is part of the receiving unit **120**. The second plasmonic nano-antenna **126** converts the electromagnetic signal **118** to an SPP signal that is converted into an electric signal by a plasmonic receiver **124** and the electric signal is then processed by an electric signal detector **122**.

As shown in FIG. **2**A, a plasmonic transmitter **200** can include a high electron mobility transistor (HEMT) **210** made with a III-V semiconductor with a graphene layer **222** (which could be a single layer of graphene or multiple layers of graphene) disposed on the gate layer **218** of the HEMT **210**. The HEMT **210** includes a source region **212** and a drain region **214**. A channel region **216** (which, in one embodiment, would typically have a length on the order of a hundred nanometers) is disposed between the source region **212** and the drain region **214**. The gate layer **218** is disposed on the channel region **216**. The channel region **216** includes a first material (such as an undoped direct band gap semiconductor, for example GaN, GaAs) and the gate layer **218** includes a second material (such as a doped semiconductor, for example InGaAs) that forms a heterojunction with the first material, which induces a two dimensional electron gas **220** in the channel region. The gate layer **218** can be biased with a bias voltage **224** to tune the response of the HEMT **210**. When a signal generator **226** applies a voltage signal between the source region **212** and the drain region **214**, the signal travels as electrons move through the electron gas layer **220**, which induces a confined plasma wave that resonates in the THz band, which induces an SPP signal **228** corresponding to the voltage signal in the interface between the gate layer **218** and the graphene layer **222**. The SPP signal **228** is then used to excite an SPP signal in a plasmonic antenna.

As shown in FIG. **2**B, a similar element can be configured as a plasmonic receiver **202**, in which a signal detector **230** is coupled to the source region **212** and the drain region **214**. In this configuration, when an SPP signal is imparted from an antenna onto the graphene layer **222**-gate layer **218** interface, a voltage signal is detectable between the source region **212** and the drain region **214** by the signal detector **230**.

As shown in FIGS. **3**A and **3**B, in one embodiment of a communication element **300**, a first constriction **342** is formed between the source region **212** and the channel region **220** by a first pair of oppositely disposed notches **340**. Similarly, as second constriction **344** is formed between the drain region **214** and the channel region **220** by a second pair of oppositely disposed notches **344**. In this embodiment, the first constriction **342** is wider than the second constriction **346**. Selection of the widths of the first constriction **342** and the second constriction **344** can be used to tune the device.

In one embodiment, as shown in FIGS. **4**A and **4**B, a plasmonic nano-antenna **420** can be coupled to a communications element **410** by coupling the graphene layer **412** on the HEMT **414** to a graphene layer **424** on a substrate **422**. The SPP signal formed in the communications element **410** (when in the transmitter configuration) excites a corresponding SPP signal in the plasmonic nano-antenna **420**, which generates a corresponding THz band electromagnetic signal. When this element is configured as a receiver, an incoming THz band electromagnetic signal induces an SPP signal in the plasmonic nano-antenna **420**, which excites an SPP signal in the communications element **410**, which in turn causes electrons to resonate in the 2D electron gas of the HEMT **414**. This results in a corresponding voltage signal being induced across the HEMT **414**.

Unlike to existing THz band sources, in this embodiment, the plasma wave is not directly radiated, but is used to induce a propagating SPP wave at the interface with the graphene layer. The oscillating image charge created at the graphene-semiconductor interface in response to the confined plasma wave oscillation in the 2DEG results in a coupled oscillating charge distribution at or near the frequency at which the system is driven. Due to the complex conductivity of graphene at THz band frequencies, this global oscillation of charge in the graphene-semiconductor interface results in an SPP wave. The propagation constant of the SPP wave, which can be tuned by modifying the chemical potential of the graphene layer, determines the SPP wave propagation length and confinement factor.

The above described embodiments, while including the preferred embodiment and the best mode of the invention known to the inventor at the time of filing, are given as illustrative examples only. It will be readily appreciated that many deviations may be made from the specific embodiments disclosed in this specification without departing from the spirit and scope of the invention. Accordingly, the scope of the invention is to be determined by the claims below rather than being limited to the specifically described embodiments above.

What is claimed is:

1. A communication element, comprising:

(a) a high electron mobility transistor including a gate layer, including:

(i) a source region;

(ii) a drain region; and

(iii) a channel region disposed between the source region and the drain region, the channel region including a first material, the gate layer being disposed on the channel region, the gate layer including a second material that forms a heterojunction with the first material, which induces a two dimensional electron gas in the channel region;

(b) a graphene layer disposed on the gate layer; and

(c) a plasmonic antenna coupled to the graphene layer, wherein the communication element is configured as a transmitter that is responsive to a transmitted electrical signal applied between the source region and the drain region, wherein the plasmonic antenna is configured to generate an electromagnetic signal corresponding to the transmitted electrical signal.

2. The communication element of claim **1**, wherein the channel region comprises a direct band gap semiconductor and wherein the gate layer comprises a doped semiconductor.

3. The communication element of claim **2**, wherein the direct band gap semiconductor comprises at least one of GaN and GaAs, and wherein the doped semiconductor comprises InGaAs.

4. The communication element of claim **1**, wherein the source region, the drain region and the channel region form a substantially rectangular shape having a first end and an opposite second end, the source region comprising a first portion across the first end, the drain region comprising a second portion across the second end, the channel region comprising a third portion disposed between the first portion and the second portion, the gate layer disposed on the third portion.

5. The communication element of claim **4**, wherein the first portion defines a first constriction between the source region and the channel region and wherein the second portion defines a second constriction between the channel region and the drain region.

6. The communication element of claim 5, wherein the second constriction is narrower than the first constriction.

7. The communication element of claim 5, wherein the first constriction is formed by at least one first notch defined by the first portion adjacent to the third portion and wherein the second constriction is formed by at least one second notch defined by the second portion adjacent to the third portion.

8. A communication system, comprising:

(a) a signal source configured to generate a transmitted signal;

(b) a plasmonic transmitter that is responsive to the transmitted signal and that is configured to generate a first surface plasmonic polariton wave signal corresponding to the transmitted signal;

(c) a first plasmonic antenna that is responsive to the first surface plasmonic polariton wave signal and that is configured to generate an electromagnetic signal corresponding to the surface plasmon polariton wave signal;

(d) a second plasmonic antenna that is responsive to the electromagnetic signal and that is configured to generate a second surface plasmon polariton wave signal corresponding to the electromagnetic signal;

(e) a plasmonic receiver that is responsive to the second surface plasmon polariton wave signal and that is configured to generate a received signal corresponding to the second surface plasmon polariton wave signal; and

(f) a signal detector that is configured to detect the received signal.

9. The communication system of claim 8, wherein at least one of the plasmonic transmitter and the plasmonic receiver includes a the high electron mobility transistor that comprises:

(a) a source region;

(b) a drain region;

(c) a channel region disposed between the source region and the drain region, the channel region including a first material;

(d) a gate layer disposed on the channel region, the gate layer including a second material that forms a heterojunction with the first material, which induces a two dimensional electron gas in the channel region; and

(e) a graphene layer disposed on the gate layer.

10. The communication system of claim 9, wherein the channel region comprises a direct band gap semiconductor and wherein the gate layer comprises a doped semiconductor.

11. The communication system of claim 10, wherein the direct band gap semiconductor comprises at least one of GaN and GaAs, and wherein the doped semiconductor comprises InGaAs.

12. The communication system of claim 9, configured as a transmitter that is responsive to a transmitted electrical signal applied between the source region and the drain region, wherein the plasmonic antenna is configured to generate an electromagnetic signal corresponding to the transmitted electrical signal.

13. The communication system of claim 9, configured as a receiver in which the plasmonic antenna is responsive to an electromagnetic signal and generates a surface plasmonic polariton wave signal corresponding thereto thereby causing an electrical signal corresponding to the electromagnetic signal that is detectable between the source region and the drain region.

14. The communication system of claim 9, wherein the source region, the drain region and the channel region form a substantially rectangular shape having a first end and an opposite second end, the source region comprising a first portion across the first end, the drain region comprising a second portion across the second end, the channel region comprising a third portion disposed between the first portion and the second portion, the gate layer disposed on the third portion.

15. The communication system of claim 14, wherein the first portion defines a first constriction between the source region and the channel region and wherein the second portion defines a second constriction between the channel region and the drain region.

16. The communication system of claim 15, wherein the second constriction is narrower than the first constriction.

17. The communication system of claim 15, wherein the first constriction is formed by at least one first notch defined by the first portion adjacent to the third portion and wherein the second constriction is formed by at least one second notch defined by the second portion adjacent to the third portion.

18. A communication element, comprising:

(a) a high electron mobility transistor including a gate layer, including:

(i) a source region;

(ii) a drain region; and

(iii) a channel region disposed between the source region and the drain region, the channel region including a first material, the gate layer being disposed on the channel region, the gate layer including a second material that forms a heterojunction with the first material, which induces a two dimensional electron gas in the channel region;

(b) a graphene layer disposed on the gate layer; and

(c) a plasmonic antenna coupled to the graphene layer, wherein the communication element is configured as a receiver that is responsive to an electromagnetic signal and generates a surface plasmonic polariton wave signal corresponding thereto thereby causing an electrical signal corresponding to the electromagnetic signal that is detectable between the source region and the drain region.

19. The communication element of claim 18, wherein the channel region comprises a direct band gap semiconductor and wherein the gate layer comprises a doped semiconductor.

20. The communication element of claim 19, wherein the direct band gap semiconductor comprises at least one of GaN and GaAs, and wherein the doped semiconductor comprises InGaAs.

21. The communication element of claim 18, further comprising a plasmonic antenna coupled to the graphene layer.

22. The communication element of claim 18, wherein the source region, the drain region and the channel region form a substantially rectangular shape having a first end and an opposite second end, the source region comprising a first portion across the first end, the drain region comprising a second portion across the second end, the channel region comprising a third portion disposed between the first portion and the second portion, the gate layer disposed on the third portion.

23. The communication element of claim 22, wherein the first portion defines a first constriction between the source region and the channel region and wherein the second portion defines a second constriction between the channel region and the drain region.

24. The communication element of claim 23, wherein the second constriction is narrower than the first constriction.

25. The communication element of claim **23**, wherein the first constriction is formed by at least one first notch defined by the first portion adjacent to the third portion and wherein the second constriction is formed by at least one second notch defined by the second portion adjacent to the third portion.

* * * * *