All-semiconductor active plasmonic system in mid-infrared wavelengths

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Abstract: Metal-based plasmonics has a wide range of important applications but is subject to several drawbacks. In this paper, we propose and investigate an all-semiconductor-based approach to plasmonics in mid-infrared (MIR) wavelength range using InAs heterostructures. Our results show that InAs heterostructures are ideal for plasmonics with the shortest plasmon wavelength among common semiconductors. More importantly, as we will show, InAs heterostructures are superior to metal-based plasmonics for MIR applications due to much reduced loss, improved confinement, and ease of tunability of resonant wavelengths through carrier density. Finally, we propose and investigate a monolithic all-semiconductor integrated active plasmonic system with active source, waveguide, and detector all integrated on a chip, realizable in a single epitaxial growth process. Such an all semiconductor based system can be advantageous not only in plasmonics, but also in active metamaterials.

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References and links


1. Introduction

Plasmonics [1,2] and metamaterials [3,4] have impacted many fields of research such as detecting and sensing [5,6], nanolasers and spasers [7–12], sub-wavelength confinement [13–15], optical cloaking [16], and other applications [17–19]. However, great challenges remain to fully realize many promised potentials, as we describe in the following. First, common metals such as gold or silver have plasmon resonances in blue or deep ultra-violate wavelength ranges. There are no available metals whose plasmon resonances are in the near or mid-infrared (MIR) wavelength range (say from 1 to 10 microns), which is an extremely important wavelength range for detection and sensing [20,21]. Second, it is highly desirable for many applications to integrate plasmonic structures with gain materials or with other dielectric materials. These applications include active metamaterials or active plasmonic system containing gain sections. But there is an intrinsic incompatibility of low-quality metal deposition with high-quality epitaxial growth of semiconductors or dielectrics. As a result, many intrinsic plasmonic properties can be masked by the poor metal quality or poor semiconductor-metal interfaces. Third, large metal loss is still a key problem for many plasmonic and metamaterial applications. In addition, the plasmonic resonance frequency (or wavelength) is fixed for a given metal. There is no tunability that could benefit many applications. Thus it is important for plasmonic applications to look into other alternatives to metals such as highly doped semiconductors.

While metallic properties of highly doped semiconductors have been used in longer wavelengths [17,20,21], their applications in shorter MIR wavelengths have not been explored. Here we demonstrate an all-semiconductor plasmonics that overcomes these challenges by using InAs heterostructures which offer the shortest plasmon wavelengths among common semiconductors with wide tunability. As we will show, the plasmonic properties of InAs-based heterostructures are superior to those of metals with much reduced optical loss and much improved modal confinement or field enhancement. Furthermore we propose and study a prototype of a monolithic all-semiconductor active plasmonic system including source, active waveguide, and detector, all realizable on a chip in a single epitaxial growth process. We believe that such metal-free plasmonic systems will have profound impact to all above applications.
2. Interband and intraband transitions in a semiconductor

For a semiconductor with high electron density, it is important to include both interband and intraband transitions, especially for narrow gap semiconductors. The relationship between electric displacement vector $D$ and electric field $E$ can be written as:

$$D = \varepsilon_0 E + P_b + P_e$$  \hspace{1cm} (1)

where $\varepsilon_0$ is the permittivity in vacuum, $P_b$ and $P_e$ are the polarizations for the interband transitions and intraband transitions (or free electrons), respectively. The free electron polarization is related to the electric field $E$ through the linear susceptibility, $\chi_e$, according to $P_e = \varepsilon_0 \chi_e E$. $\chi_e$ can be approximated by the Drude model:

$$\chi_e(\omega) = -\frac{N e^2}{\varepsilon_0 m (\omega^2 + i\omega/\tau)} = -\frac{\varepsilon_0 \omega_p^2}{\omega^2 + i\omega/\tau}$$  \hspace{1cm} (2)

where $N$ is the free electron concentration, $e$ is the electron charge unit, $m$ is the effective mass of electrons in semiconductor and $\tau$ is the free electron relaxation time. The plasmon frequency $\omega_p$ is given by

$$\omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 \varepsilon_{\infty} m}}$$  \hspace{1cm} (3)

where $\varepsilon_{\infty}$ is the semiconductor dielectric constant for $\omega \gg \omega_p$. The dielectric function corresponding to the interband transitions is given by $\varepsilon_b = 1 + \chi_b$, which can be calculated using a semi-empirical expression for undoped or lightly doped semiconductors [22]. This model used a multi-transition best fit to the experimentally measured dielectric function to get $\varepsilon_b$. Semiconductors with small effective mass in conduction band, such as InSb or InAs, are easy to become degenerate at high electron density. In that case the absorption cannot happen near band edge since the bottom of conduction band is fully or nearly fully occupied by electrons, as was first noticed by Burstein [23]. The absorption coefficient, $\alpha$, can be given by taking into account of the occupation probabilities of electrons and holes, $f_e$ and $f_h$, respectively:

$$\alpha = \alpha_0 (1 - f_e) (1 - f_h) - f_e f_h = \alpha_0 (1 - f_e - f_h)$$  \hspace{1cm} (4)

where $\alpha_0$ is the absorption coefficient in undoped or lightly doped semiconductor. The absorption coefficient is related to the imaginary part of semiconductor dielectric constant by $\varepsilon_b^* = n_b c \alpha / \omega$, where $n_b$ is the background refractive index and $c$ is the speed of light in vacuum. Finally the total dielectric constant is given as $\varepsilon_r = \varepsilon_b + \chi_e$.

3. Plasmonic features of InAs heterostructures

Carrier densities that can be introduced in common semiconductors are orders of magnitude lower than in metals, so that plasmon resonances in doped semiconductors are typically in wavelength range longer than 10 microns [17]. One of the key tasks for semiconductor plasmonics is to identify semiconductors and related heterostructures that can be highly doped or injected, such that the plasmon resonances can be in the MIR wavelength range. To compare the relative merits of common semiconductors, we plot in Fig. 1(a) the corresponding plasmon wavelengths ($\lambda_p = 2\pi c / \omega_p$) as a function of electron density. As we can see, InAs has the shortest plasmon wavelength for a given electron density. Even though all semiconductors can in principle be doped for plasmonic applications, the required doping
levels are typically too high to be practical, especially for short wavelength applications. From Eq. (3), it is clear that InAs is the best candidate to provide the largest plasmon frequency, since InAs is among few semiconductors with the smallest electron mass. Figures 1(b) and 1(c) show respectively the real and imaginary part of dielectric constant \( \varepsilon_r \) of InAs from 2 to 10 \( \mu m \) for different electron concentrations. Heavily doped InAs becomes metallic, as indicated by the negative real part of \( \varepsilon_r \) in the entire wavelength range shown. Higher electron density makes the metallic property more pronounced. Another important advantage of InAs is that it can be grown lattice matched with AlSb and GaSb [24–27] to form several interesting heterostructures, as shown in Fig. 1(d), where a “broken-gap” InAs/GaSb structure and a deep AlSb/InAs/AlSb quantum well are shown. Both of these structures allow high electron density to be introduced in the InAs layer at equilibrium without intentional doping [25,26]. The broken-gap lineup is a spatial “semimetal” structure with conduction band edge (in InAs) lower than the valence band edge (in GaSb), similar to the common semimetals in k-space. Electrons and holes thus are separated spatially, avoiding major recombination in InAs.

To achieve high electron density, electrical bias has to be applied. Here we consider a p-GaSb/n-InAs/p-GaSb three layer structure as an example, as shown in the inset of Fig. 2. We performed a two-dimensional (2D) simulation of this structure using ATLAS [28] assuming InAs layer is uniformly doped at \( 6 \times 10^{17} \text{ cm}^{-3} \) and GaSb layers are doped at \( 5 \times 10^{18} \text{ cm}^{-3} \). Forward bias is applied on both GaSb layers. The electron density at the edge and in the middle of InAs layer as a function of bias is shown in Fig. 2 by black and red curves, respectively. Without bias, the electron density at the edge of InAs layer is \( 8.5 \times 10^{17} \text{ cm}^{-3} \) and that in the middle of InAs layer is \( 7.7 \times 10^{17} \text{ cm}^{-3} \). Even though higher doping densities can be introduced in each of these layers, these density levels are still too low. The electron density throughout the InAs layer is uniform but not large enough for plasmonic applications. As bias increases, the density at the edge increases faster than that in the middle of InAs layer, resulting in non-uniform distribution in InAs layer. However, since the strongest intensity of a surface mode is usually located at the InAs/GaSb interface, the electron density at the edge of
InAs layer is more important for plasmonic application. We can see that the electron density at the edge reaches $1 \times 10^{20}$ cm$^{-3}$ at a bias of 4 V, a large enough value for our plasmonic application.

![Graph showing electron density as a function of bias for a GaSb/InAs/GaSb structure.](image)

**Fig. 2.** Electron density as a function of bias in a GaSb/InAs/GaSb structure (inset). The black and red curves show respectively the electron density at the edge and in the middle of InAs layer. The thickness of each layer in the GaSb/InAs/GaSb structure is shown in the inset.

To demonstrate the advantages of plasmonic features of InAs structures, we consider a prototype surface plasmon polariton (SPP) structure: a bi-layer structure with a heavily doped InAs layer (dielectric constant $\varepsilon_m$) as a metallic layer interfaced with a GaSb layer with a dielectric constant $\varepsilon_s$. Assume the SPP wave propagates along the InAs/GaSb interface in the $z$ direction, the propagation wavevector $k_z$ is given by $k_z = \frac{\omega}{c} \sqrt{\varepsilon_s \varepsilon_m / (\varepsilon_s + \varepsilon_m)}$. The quality factor (Q factor) of this mode can be obtained via the definition [29]:

$$Q = \frac{\omega P_{\text{stored}}}{P_{\text{dissipated}}} = \frac{\omega}{2k_z^* \gamma_{E,z}}$$  \hspace{1cm} (5)

where $k_z^*$ is the imaginary part of the propagation wavevector and $\gamma_{E,z}$ is the average energy velocity of the mode [14]. Figure 3 shows the Q factors as a function of wavelength of a SPP mode in an InAs/GaSb structure with different electron concentrations, in an Ag/GaSb structure, and in an Au/GaSb structure. The dip (minimum) in each curve corresponds to the SPP resonance. We can see that the Q-factor of InAs/GaSb structure increases with electron density on the longer wavelength side of plasmon resonance. The situation becomes more complicated below plasmon resonance wavelength. One important result is that the Q factor of InAs/GaSb structure is several times larger than that of Ag/GaSb and Au/GaSb structures. Therefore, highly doped InAs structure is an excellent plasmonic waveguide and is superior to typical metal-based structures.
Fig. 3. Quality factors vs. wavelength of a SPP mode in an InAs/GaSb structure with different electron concentrations (cm\(^{-3}\)), in an Ag/GaSb structure, and in an Au/GaSb structure.

It is interesting to see how tightly a mode can be bound at the InAs/GaSb interface, since tight confinement of a mode is important for nanophotonic applications. Figure 4 shows normalized energy density and power flux (absolute value) profile across the interface of the InAs/GaSb structure for different electron concentrations in InAs at 3 and 5 \(\mu\)m, respectively. We can see from Figs. 4(a) and 4(b) that the energy and power densities for InAs/GaSb at electron density 6 \(\times\) 10\(^{19}\) cm\(^{-3}\) are almost flat in both InAs and GaSb layers. This is because the working wavelength is shorter than the SPP resonance wavelength so that SPP mode is very loosely bound at the interface. The situation is the same for the case with density 2 \(\times\) 10\(^{19}\) cm\(^{-3}\) in Figs. 4(c) and 4(d). The operating wavelength thus has to be longer than the SPP wavelength for better SPP localization. In order to quantitatively describe the mode confinement at the interface, we introduce effective widths \(W_t\) across the interface as the sum of the width in InAs layer, \(W_m\), and that in GaSb layer, \(W_s\) (see Figs. 4(a) and 4(b)). They are defined as the distance from the interface through which the energy or power decays to \(e^{-2}\) of their values at the interface. The three widths measured at the working wavelength of 3 \(\mu\)m are listed in Table 1. The effective widths for InAs/GaSb waveguide at density 6 \(\times\) 10\(^{19}\) cm\(^{-3}\) are extremely long, corresponding to the flat curve in Figs. 4(a) and 4(b). For larger electron density, the effective widths are small. The total effective width at density 8 \(\times\) 10\(^{19}\) cm\(^{-3}\) is the smallest one, because the working wavelength is very close to but still longer than the SPP resonance wavelength where the SPP mode has the best confinement. The total effective width at 73 nm is one fortyeth of the working wavelength in this case, representing a huge compression of the effective wavelength. There are similar conclusions for the case with working wavelength at 5 \(\mu\)m, with the required density somewhat smaller. Since the Q factor at the SPP resonance is the smallest (see Fig. 3), the electron density in InAs needs to be well controlled to meet the requirement of both quality and confinement in a waveguide design.

<table>
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<tr>
<th>Electron density (cm(^{-3}))</th>
<th>6 (\times) 10(^{19})</th>
<th>8 (\times) 10(^{19})</th>
<th>1 (\times) 10(^{20})</th>
<th>2 (\times) 10(^{20})</th>
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<td>38</td>
<td>95</td>
<td>218</td>
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<tr>
<td>(W_m) (nm)</td>
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<td>54</td>
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<tr>
<td>(W_s) (nm)</td>
<td>&gt;2 (\times) 10(^4)</td>
<td>73</td>
<td>155</td>
<td>272</td>
</tr>
</tbody>
</table>
4. All-semiconductor plasmonic system

The most interesting aspect of an all-semiconductor plasmonic structure is the possibility of monolithically growing an entire plasmonic system with various components on a chip. To illustrate this exciting aspect, we propose and conduct a design study of an all-semiconductor plasmonic system consisting of a SPP source, a waveguide with integrated amplifiers, and a detector, as shown in Fig. 5(a). All three components can be grown in a single epitaxial growth process and each component can be then defined lithographically. The high electron density (on the order of $10^{20} \text{ cm}^{-3}$) in InAs can be achieved by electrical bias of the doped structures. An active structure is needed to provide gain in the source and amplifier. In addition to InAs and GaSb, AlSb can be used as a barrier material. The layer structures of all three components are identical and shown in Fig. 5(b) where the material composition, doping types, thickness and polarity of electrodes of each layer are also shown. The active region consists of p-AlSb/i-InAs/n-AlSb triple layers, with the intrinsic InAs layer serving as the gain layer. This structure has been shown to be able to produce strong interband gain despite being a type-II structure for the undoped system [27]. The plasmonic structure consists of p-GaSb/n-InAs/p-GaSb triple layers. SPP mode is formed and propagating at the two n-InAs/p-GaSb interfaces, as we studied above in Section 3. The overall working principle of this system is illustrated in Fig. 5(c).

**Source:** The bias $V_s$ is positive in the source, electrons and holes are thus injected into the i-InAs layer. Optical dipoles formed by the electron-hole pairs in this layer then recombine to excite and transfer energy preferentially to the SPP mode at the two p-GaSb/n-InAs interfaces [30]. The SPPs are thus generated in the source. If a time-varying signal voltage $V_S(t)$ is added to $V_s$, the amplitude of the SPPs will be modulated according to the strength of the signal.

**Amplifier:** The amplifier functions similar to the source. The bias $V_1$ has the same positive constant value $V_0$ as that in the source. When passing through the amplifier, the SPPs from source will acquire energy emitted from the electron-hole pairs in the i-InAs layer and get amplified.

**Detector:** The bias $V_1$ in the detector is negative, so the i-InAs layer is depleted. The incoming SPPs are then absorbed by InAs layers of the detector. The portion of the energy absorbed by the i-InAs initiates the generation of the electrons and holes in this layer which...
can be collected through the electrodes of the reversely biased p-i-n structure. Since the density of generated carriers is proportional to the amplitude of the arrived SPPs, the signal from the source is demodulated and detected by the detector. Note that the gain spectrum provided by the active region has a peak frequency larger than InAs bandgap, as shown earlier [27]. Therefore, most of the energy of the SPP mode can be absorbed by the InAs layer in the detector.

![Diagram of the proposed plasmonic system](image)

**Fig. 5.** All-semiconductor active plasmonic system. (a) Schematic of the proposed plasmonic system consisting of a SPP source, a waveguide with amplifiers and a detector. (b) The layer structures of all three components of this system. The material composition, doping type, thickness and polarity of electrodes of each layer are also shown. (c) Illustration of the working principle of the system.

We performed a 2D simulation of this system using ATLAS assuming the layers in the active structure are uniformly doped at $2.5 \times 10^{18} \text{ cm}^{-3}$ and the layers in the plasmonic structure are doped at $5 \times 10^{18} \text{ cm}^{-3}$. The electron and hole densities were calculated at $V_1 = 0.8 \text{ V}$ (source and amplifier) and $V_2 = 5 \text{ V}$, and their profiles are shown in Fig. 6. The metallic InAs layer is located from $x = 90$ to $110 \text{ nm}$. At the edge of this layer, the maximum electron density is about $1.5 \times 10^{20} \text{ cm}^{-3}$ while the hole density is lower than $1 \times 10^{14} \text{ cm}^{-3}$. This situation is exactly what we need for the InAs application as a metal. In the middle of the metallic InAs layer ($x = 100 \text{ nm}$), the minimum electron density is about $4.2 \times 10^{19} \text{ cm}^{-3}$, ensuring the maximum real part of the dielectric constant of InAs is still negative in the layer. Therefore this InAs layer can be treated as a pure metallic layer. Note that the hole density at the edge of GaSb layer is higher than the electron density at the edge of InAs layer, the metallic property of GaSb due to hole absorption thus needs to be considered. The collective motion of high-density holes can also be approximated by Drude model and the treatment of dielectric function of GaSb is similar to that shown in Section 2 for InAs. The InAs gain layer is located from $x = 50$ to $70 \text{ nm}$. The carrier density on the right half of this layer is not uniform because holes are preferentially swept from the middle AlSb layer into the GaSb layer on the right instead into the InAs layer on the left, leading to low hole density on the right half of InAs gain layer. The carrier density is, however, high and uniform enough on the left half of this InAs layer, which can still provide high material gain to the whole system.
Fig. 6. Electron and hole density profiles along x axis at $V_1 = 0.8 \text{ V}$ and $V_2 = 5 \text{ V}$ in the plasmonic system.

Fig. 7. Modal pattern of a SPP mode in the plasmonic system. (a) Power flux pattern of a SPP mode at $3.3 \mu\text{m}$ in the plasmonic waveguide with a length 500 nm in z direction. (b) Normalized power flux (absolute value) profile taken from the dashed line in Fig. 7(a).

The non-uniform dielectric constant profile in the metallic InAs layer and its adjacent GaSb layers was calculated by using the actual electron and hole density profiles from the simulation. The results then were used in a 2D electromagnetic mode analysis by COMSOL [31] to find the SPP modes in the structure with a length 500 nm in z direction. Note that only the SPP mode is analyzed in this work since its highly-localized feature ensures the design of a system whose transverse size (the direction vertical to the wave propagation) can be on nanoscale. Other modes like TE mode, however, will spread out everywhere in the system consisting of layers with thickness of only a few tens of nanometers. The material gain in the InAs gain layer can be estimated from [27]. The power flux pattern of a SPP mode at an operating wavelength of $3.3 \mu\text{m}$ is shown in Fig. 7(a). The mode propagates from left to right.
and increases exponentially due to the gain provided by the active structure. The normalized power flux (absolute value) profile taken at the location of the dashed line in Fig. 7(a) is shown in Fig. 7(b). We can see that most of the power of the structure travels outside the metallic InAs layer but is tightly bound at the InAs/GaSb interfaces. The effective width across the left-hand-side layers of the metallic InAs layer is about 26 nm. The propagation length \( (1/(2k_\text{eff}^2)) \) of the SPP mode in the waveguide without amplifier is below 10 \( \mu \text{m} \).

However, since the amplifier provides the SPPs with a net modal gain \((-2k_\text{eff}^2)\) of 26.3 cm\(^{-1}\), the SPPs can propagate over hundreds of microns if multiple-amplifier configuration is used. This structure is thus suitable for the nanoscale SPP waveguiding at 3.3 \( \mu \text{m} \). The propagation length and the layout of the amplifiers required depend on the operating wavelength. To provide a gain at longer wavelengths, InAsSb alloy can be also used so that the operating wavelength can be somewhat further above the plasmon resonance wavelength of the InAs plasmonic structure.

5. Conclusion

In summary, we have investigated the plasmonic properties of InAs-heterostructures by using the Drude model. Our result showed that InAs-heterostructures are superior to other common semiconductors and metals for applications in plasmonic structures and metamaterials for MIR wavelengths. The SPP modal properties have been studied in detail using an InAs/GaSb bi-layer structure for different electron concentrations in the InAs layer. Finally, we proposed and studied a prototype system of a monolithic all-semiconductor integrated plasmonic system on a chip, realizable in a single epitaxial growth process. The significance and impact of the proposed plasmonic heterostructures and integrated system can be appreciated in several ways. First the InAs-based structures fill an important bandgap window between 2 and 8 microns for plasmonic applications in MIR range. While common metals can be used for MIR wavelength as good mirrors, but they cannot be used as plasmonic structures, since there is almost no localization near the metal surfaces at these long wavelengths. The easy tunability of plasmonic wavelength by simply changing the bias voltage is an important advantage of semiconductor based system. This allows a fabricated plasmonic system to be able to tune to different wavelength “on the fly”, a significant important feature for adaptable plasmonic system. The available semiconductors such as GaSb and AlSb that are lattice matched to InAs can work as barrier materials or allow easy design of active source, amplifying waveguide, and detector, all based on the same substrate. Thus an entire plasmonic system can be grown in a single epi-process. This is a significant advantage compared to plasmonic or metamaterial structures that use a combination of metals and semiconductors, since high quality semiconductors have to be grown epitaxially, while metals are typically deposited in a thermal process with much poorer crystal quality. Our all-epitaxially grown integrated plasmonic system in a single process can offer unprecedented quality and reliability. The low loss (or high quality factor) of InAs is another important advantage. Such metal-free, all-epi-growth approaches are especially important for metamaterials where more complicated structures on deep-subwavelength scales with higher fabrication precision are required. In addition, active gain materials can be integrated with the same epitaxial growth. All these remarkable features will make the proposed all-semiconductor active plasmonic system the most promising ones for tunable applications in MIR range. We believe that such all-semiconductor plasmonic systems will have a profound impact to many applications mentioned in this paper.

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