Design and Simulation of an Electrically Pumped SPASER

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Abstract: In this investigation, a novel SPASER is designed and simulated which uses a forward biased pn junction to induce population inversion condition. Simulations are performed by means of SILVACO software. In the proposed structure, the active region is considered as a direct bandgap material (InGaAs) and a larger bandgap material (InP) is used for p and n regions to form heterojunctions. This pn junction is in contact with gold and surface plasmons propagate along their interface. Free space wavelength of the oscillations of surface plasmons is 1550nm that is used in photonic devices, frequently. To form the resonance cavity of the SPASER, two high reflective mirrors are placed at the ends of the plasmonic waveguide. Applied forward voltage and absorption coefficient of the SPASER are 1.2V and -0.33cm$^{-1}$, respectively. Thus, the optical gain for a 50 microns cavity length is 1cm$^{-1}$. Moreover, the power consumption of the proposed device at these conditions is 1.2mW. The output plasmonic power is 0.6mW which yields 50% power efficiency.

Keywords: Surface Plasmon; SPASER; Electrical pumping; pn junction.

1. Introduction

In the electronic circuits, electrons as the charge carriers, are transported. However, speed of transmitting data from one point to another is limited because of the losses imposed by metallic wires and interconnections. Photonics is an alternative to overcome this limitation by means of optical circuits and optical fiber telecommunications. Although the photons move faster than electrons, they have large wavelengths. Hence, because of diffraction limit they are not usable in nanometer devices. Nowadays, Plasmonics removes these limitations by taking the advantages of both electronics and photonics. Since, the surface plasmons have shorter wavelengths than photons, the integration of plasmonic devices beside the electronic ones on a single chip is possible [1,2].

Plasmonics confines electromagnetic energy to sizes well below the diffraction limit. Plasmon is the interaction of electromagnetic energy (light) and free electrons of metals or metallic nanostructures [3]. Plasma is a state of the matter in which electrons are separated from the atoms. Free electrons of a metal have a similar condition. Electromagnetic waves excite this electrons and this interaction propagates in the metal structure [4,5].

Oscillations of electrons at the interface between a metal and a dielectric are called surface plasmons which their propagation is affected greatly by the properties of the interface [6]. Nano plasmonics studies the performance of surface plasmons (SPs) in metallic nano structures [7]. SPs in nano structures with sizes comparable to or smaller than the wavelength of the SP, are called local surface plasmons. In this case, electric field at the surface of the nano structure significantly increases [8]. This is a way to confine the light energy to nano meter scales. Thus, plasmonics can be used to form strong local electric fields [4,9-10], and was the topic of many studies in recent years [11]. One of the major challenges in plasmonics is the losses imposed by metals. Refraction index of dielectrics is a positive real number, while for metals this value is a complex number with negative real part. The imaginary part of refraction index is the reason of losses. Thus, SPs are attenuated during propagation [12] and their propagation length is limited by these losses [13].
In 2006, Ozbay described that in all plasmonic waveguides there is a trade-off between confinement factor and the propagation loss, which is considered as the main challenge of plasmonics [13]. If the real part of the refractive indices of the metal and dielectric as the forming materials of the interface, increases, confinement factor increases, too. Also, by the increment of imaginary part of the refractive indices, the loss would be increased. High confinement is desirable but losses are not.

Many structures have been proposed to overcome this trade off. One of them uses a simple metal-insulator interface [14]. Another is an Insulator-Metal-Insulator structure [12]. If the metal layer, is thin enough, two plasmonic modes at each interface interact with each other and a combined mode is formed [12]. These structures also include metal strip [15], grooved [16], hybrid [17,18] and dielectric-loaded [19,20] plasmonic waveguides. While most of the papers have modified the cross section structure of the waveguide, one hybrid waveguide with longitudinal structure has been proposed [21]. But none of these structures could overcome the trade-off between confinement and loss, perfectly [22].

The only promising way to increase the confinement and the propagation length simultaneously, is by means of an appropriate gain medium [12,13]. There are several investigations that have used this method. Among them is the usage of quantum dots in polymers [23], dye molecules in solutions or polymers [24,25], and multiple quantum well structures [26]. These methods have developed in recent years leading to the insertion of SPASERs in nano scales [12].

2. SPASER

SPASERs are like lasers but instead of photons, SPs are generated in them [27,28]. Scaling the lasers down to nanometers was impossible due to diffraction limit [29,30], but for SPs, the wavelengths are smaller than photons and the diffraction limit is less challenging. Thus, SPASERs would be fabricated in much smaller dimensions than lasers [31]. Down scaling not only improves the performance, but also reduces the costs [10].

Similar to lasers, in the structure of a SPASER there is a gain region to supply energy for SP mode. This gain region should be pumped externally. It can be implemented by means of another laser light with higher frequency. For example, SP oscillations may be in the frequency range of infrared but pumping must be in the range of visible light or ultra violet [27]. Sufficient pumping in the gain region leads to population inversion which is necessary for stimulated emission. There is a threshold pumping level which above that the stimulated emission would be more than the spontaneous emission. In this condition, the pumping power should cancel all the losses in the structure [32]. It is notable that as the cavity is smaller, it has lower threshold level in addition to higher speed of operation [33].

Usually, in optical pumping, device is illuminated entirely which leads to unnecessary pumping. Instead, waveguides can be used in transferring the light energy to the desired region. But optical waveguides are diffraction limited, too. Consequently, in nano scale integrated circuits, there is not enough space for waveguides. While, most of the SPASERs are pumped optically, electrical pumping is a promising method in transferring energy to SP modes [34].

3. The SPASER Designing

Here, we have used a forward biased pn junction to induce the population inversion condition. Active region is placed between n-type and p-type semiconductors. In forward bias, carriers are injected into active region and their recombination releases an energy that can be coupled to the oscillations of electrons at the interface of the gold and p-type region.
3.1. Design Parameters

In the active region, we used a direct bandgap semiconductor to increase radiative recombination. \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) has a direct bandgap of 0.75eV which is suitable for free space wavelength of 1550nm. For p-type and n-type regions, InP have been used that is lattice-matched to \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \).

For the anode contact, Gold with the thickness of 100nm have been used as it has prominent plasmonic features. The considered anode contact is thick enough to separate plasmonic modes above and below of itself. On the other hand, its thickness is low enough to minimize the fabrication time and cost [22].

Dimensions of semiconductor regions are probed to sufficient energy coupling to overcome the losses of the SP mode. Thickness of the p-type region is considered to be smaller to place the active region near the gold surface and the thickness of InP as the bottom layer is sufficient. Considering the trade-off between the amplification enhancement, power consumption reduction and threshold current decrement, the cavity length of 50um is selected for the proposed structure. Moreover, two mirrors with the reflectivities of 100% and 99% are placed at the ends of the cavity. The SP mode gets amplified between these mirrors and finally exits from the 99% mirror side. The direction of SP mode propagation is shown in figure 2.
In fiber optic telecommunications, lights with free space wavelength of 1550nm are favorable because the attenuation of silica in this wavelength is minimum. Consequently, many photonic devices are designed and fabricated to operate in this wavelength. Specifications of the materials used in this structure at the wavelength of 1550nm are listed in table 1.

Table 1. Bandgap, permittivity and refraction indices of the structure materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>(\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As})</th>
<th>\text{InP}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band-gap Energy (E_g)</td>
<td>0.75ev</td>
<td>1.35ev</td>
</tr>
<tr>
<td>Relative permittivity (\varepsilon_r)</td>
<td>13.94</td>
<td>12.5</td>
</tr>
<tr>
<td>Refractive index (n)</td>
<td>3.56</td>
<td>3.18</td>
</tr>
</tbody>
</table>

Below and above the active region, two heterojunctions are formed as the bandgap of InP is wider than \(\text{InGaAs}\). Consequently, there would be a potential barrier in front of the electrons and holes that are entered the active region. These two junctions operate similar to a potential well and confine the carriers to the active region. On the other hand, the refraction index of \(\text{InGaAs}\) is higher than InP which leads to the confinement of the light in the active region. To confine the SP mode laterally, a low index insulator such as \(\text{SiO}_2\) is used.

The contact of gold and p-type semiconductor should be an ohmic one. So the p-type region is highly doped to \(10^{18}\text{ cm}^{-3}\). Doping of the n-type region should be high enough to prepare electrons in the active region, but due to the second order effects such as mobility degradation and formation of band tail, its value is considered to be \(10^{17}\text{ cm}^{-3}\). Moreover, doping of the active region should be as low as possible to minimize the diffusion of electrons to p-type semiconductor, which may reduce the laser efficiency [35].

Energy band diagram of the materials before the formation of the junctions is shown in figure 3. After formation of the junctions and diffusion of carriers, active region is fully depleted due to its low doping level compare to the neighboring semiconductors. This is beneficial to induce the population inversion and enhances the efficiency. The band structure of the junctions is shown in figure 4.
Fig. 4. Band structures of the device.

Differences between the conduction and valence bands edges are observable in this figure. Consequently, electrons and holes moving toward the p-type and n-type regions encounter a barrier of $\Delta E_c$ and $\Delta E_v$, respectively.

3.2. Applying Voltage for the Operation of SPASER

In order to induce population inversion in the structure, pumping is required. Thus, the pn junction should be forward biased. As the applied voltage increases, more strong population inversion is induced, but also power consumption is increased. Following equation defines the attenuation coefficient which is related to populations of electrons in energy levels.

$$\Delta I = -a I \Delta x = I(x + \Delta x) - I(x)$$

(1)

In the limit, equation 1 leads to the following equation where $B_{21}$ indicates the stimulated emission coefficient, $c_0$ is the speed of light in vacuum condition, $n$ denotes the effective refractive index and $\nu$ is the frequency of the light beam.

$$\nu^2 B_{21} = \frac{a c_0}{h} = (N_2 - N_1)$$

(2)

At thermal equilibrium, $N_1 > N_2$ and the absorption coefficient is positive. Thus, light would be absorbed by the material. To induce population inversion, we should have $N_2 > N_1$ as the condition where the absorption coefficient is negative. This means that light gets amplified and the gain of is defined as the negative of the absorption [36]:

$$g = -a = (N_2 - N_1) \frac{B_{21} h}{c_0}$$

(3)

Absorption coefficient of the simulated device is shown in figure 5. As a result of this figure, absorption coefficient for the applied voltages less than 1.1V is positive that indicates negligible stimulated emission, while
for the voltages beyond 1.1V lasing happens. In forward voltage of 1.2V, local optical gain of the active region is 0.33 cm\(^{-1}\).

![Graph showing absorption coefficient of the SPASER as a function of applied voltage.](image)

**Fig. 5.** Absorption coefficient of the SPASER as a function of applied voltage.

Considering this observation, the gain of SP mode would be expressed as follows where \(L\) is the length of the cavity. [35]:

\[
G_{so} = \exp(gL)
\]  

(4)

Hence, for the cavity length of 50\(\mu\)m, the gain of the SP mode would be obtained as 1cm\(^{-1}\). The gain of the structure as a function of voltage is shown in figure 6 which states that the gain increases to reach the threshold condition. Next, the gain curve saturates at a value equal to the cavity loss.
4. Electrical Pumping Results

Large amounts of carrier concentration in active region is necessary for the correct operation of the SPASER. This increases the recombination rate which is shown in figure 7. Considering this figure, it is conclusive that recombination is restricted just to the active region.

The intensity of SP mode is shown in figure 8. A large portion of the SP mode is observed in the active region but slightly is diffused to the surroundings, too. The reason relates to the confinement of SP mode and charge carriers in the active region.
Fig. 8. Distribution function of the SP mode intensity.

The $H_z$ component of the magnetic field is shown in figure 9 where the existence of the SP mode in metal is observable. Just a little portion of the SP mode is in the metal which imposes loss to the mode and yields to the efficiency decrement.

Fig. 9. Distribution of the $H_z$ component of the SP mode magnetic field.

Figure 10 demonstrates the current-voltage characteristic of the SPASER. In forward bias voltage of 1.2V, the current of 20µA flows from each micron of the SPASER length. Regarding the 50µm length of the SPASER, total current would be 1mA. Thus, power consumption is 1.2mW.
Output plasmonic power of the SPASER as a function of applied voltage is shown in figure 11. Output power at the forward voltage of 1.2V, is 0.6mW. Thus, the efficiency of the SPASER is obtained equal to 50%.

5. Conclusion

In this paper, a SPASER is designed with electrical pumping of a pn junction. An important challenge of plasmonic structures is their losses imposed by metal which reduces the propagation length. To overcome this challenge, a gain medium is proposed that induces population inversion and enhances the stimulated emission significantly. For the active region of our structure, $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ have been used and the p-type and n-type regions are selected as InP.
The pn junction of the structure is forward biased and the bandgap difference of the active region and p-type and n-type semiconductors, confined the carriers in the active region. Output SP mode wavelength is 1550nm which is near the peak of the InGaAs material gain curve.

Absorption function has been considered, where the absorption is negative and correspond to amplification process is determined. Gain of the SP mode for a cavity length of 50μm is 1cm⁻¹. As the total current of the device is 1mA at forward voltage of 1.2V which corresponds to 1.2mW power consumption and the output SP power at the same bias voltage is 0.6mW, the efficiency of the proposed SPASER is 50%.

Declarations

Funding: Not Applicable.

Conflicts of interest/Competing interests: Not Applicable.

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Code availability: On request.

Authors’ contributions: Not Applicable.

Ethics approval: Not Applicable.

Consent to participate: Not Applicable.

Consent for publication: Not Applicable.

References

Figure 1

The structure of a SPASER pumped by a pn junction.
Figure 2

Three dimensional view of the designed SPASER pumped electrically by a pn junction.

Figure 3

<table>
<thead>
<tr>
<th>Inp</th>
<th>$In_{0.53}Ga_{0.47}As$</th>
<th>Inp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_c$</td>
<td></td>
<td>$E_c$</td>
</tr>
<tr>
<td>$E_v$</td>
<td>$N_{A1} = 10^{18}$</td>
<td>$E_f$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.35$ ev</td>
</tr>
<tr>
<td></td>
<td>$N_{A2} &lt;&lt; N_{A1, N_D}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.75$ ev</td>
</tr>
<tr>
<td></td>
<td>$N_D = 10^{17}$</td>
<td>$E_v$</td>
</tr>
</tbody>
</table>
Band structures of the semiconductors before the formation of the junctions.

\[
\text{Inp} \\
E_\text{c} \uparrow \quad \Delta E_c \quad \downarrow \quad \text{In}_{0.53} \text{Ga}_{0.47} \text{As} \\
E_\text{v} \downarrow \\
N_A = 10^{18} \\
\quad \Delta E_v \\
E_\text{c} \uparrow \quad \downarrow \quad E_\text{v} \\
N_D = 10^{17} \\
\]

Figure 4

Band structures of the device.
Figure 5

Absorption coefficient of the SPASER as a function of applied voltage.
Figure 6

Gain of the SP mode versus the bias voltage.
Figure 7

Distribution function of the recombination.
Figure 8

Distribution function of the SP mode intensity.
Figure 9

Distribution of the Hz component of the SP mode magnetic field.
Figure 10

Distribution of the Hz component of the SP mode magnetic field.
Figure 11

Output plasmonic power versus the applied voltage.