Development of a Solar-Pumped Laser Diode

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1. Introduction
Space solar power satellites (SSPS) using laser technology are being studied at NAL. The concept of a Laser Energy Network (LE-NET) has been proposed by NAL, consisting of a wireless solar power supply system in space for distant end users[1]. A solar-pumped laser (SPL) is a key technology for the SSPS. It should have a simple and light-weight system, compared with the conventional combination of solar cell and electrical-drive laser equipment. The SPL absorbs sunlight directly, pumping the laser material that then emits laser light. It functions as a converter from incoherent solar light to coherent laser light suitable for long-distance transmission. The conceptual design of the SPL, which will use a semiconductor for high conversion efficiency, is discussed in this paper.

2. Why a semiconductor?
A semiconductor can absorb energy from photons whose energy exceeds its energy band gap, and do this in a thin layer due to its small absorption coefficient (on the order of $10^{-4}$ cm$^{-1}$). In contrast, other candidates for solid laser materials have narrow absorption spectra for the solar spectrum, with quite large absorption coefficients (on the order of 1 cm$^{-1}$). This absorption feature of semiconductors can ideally give about a 40% conversion efficiency from sunlight to laser light, based on calculations of quantum efficiency[2].

III-V compound alloys have advantages for photo-electronic devices because they are a direct-transition type giving large absorption and emission coefficients, unlike indirect types such as silicon and germanium. An aluminum gallium arsenic (AlGaAs) compound system covers wavelengths from the visible to the near infrared region, which is most suitable for the SSPS[2]. Since this AlGaAs is a lattice-matched system, the aluminum mole fraction $x$ in Al$_x$Ga$_{1-x}$As can control the band gap energy. We currently utilize well-developed fabrication techniques in AlGaAs-LD products, mainly for compact disc players. The challenge is to design a structure to extract the maximum performance from the SPLD.

3. Transfer of the carriers to the active layer
Carriers produced by absorption of sunlight should be efficiently concentrated into the active layer to emit laser light. A step-like potential structure previously proposed[3] is shown in Fig. 1 (a). The solar light comes from the left side and is absorbed in the Al$_x$Ga$_{1-x}$As layer sandwiching the active layer of the GaAs. The absorbing layer is covered by confinement layer of AlAs, with a higher band gap energy. This structure lets the carriers in the absorption layer flow into the active layer by diffusion. For efficient concentration of carriers, the hole diffusion length of $L_h$, determined by the carrier diffusion coefficient $D_h$ and the hole life time $\tau_h$, should be larger than the thickness $d_{flat}$ of the absorption layer,

$$L_h = \sqrt{D_h \cdot \tau_h} \geq d_{\text{flat}}$$  \hspace{1cm} (1)

This relationship means that the hole diffusing through the absorption layer can reach the active layer before recombination with an electron, i.e. within its lifetime. Using Einstein’s relation: $D/\mu = kT/e$, Eq. (1) can be written as

![Fig.1 Potential structures](image-url)
\[ d_{\text{flat}} \leq \sqrt{\frac{\mu \cdot kT}{e}} \cdot \tau_h \]  

(2)

where \( \mu \) is the mobility. This gives the absorption layer thickness needed for transferring the carrier into the active layer without excessive carrier extinction on the way.

The drift process is used in our proposal to drive carriers in addition to the diffusion process, by using a graded potential (GP) structure in the absorption layer. The mole fraction \( x \) of aluminum in \( \text{Al}_x\text{Ga}_{1-x}\text{As} \) can control the band gap energy. A continuously changing band-gap-energy structure can be fabricated by continuously changing the mole fraction in the epitaxial growth process. Coincidence of the Fermi level in the layers gives the GP structure shown in Fig. 1 (b). The transit time \( (T_{\text{transit}}) \) of the carrier from one side of the absorption layer to the other (the one contacting the active layer) should be less than the lifetime of the drifting carrier,

\[ T_{\text{transit}} = \frac{d_{\text{GP}}}{v_{\text{drift}}} \leq \tau_h \]  

(3)

where \( d_{\text{GP}} \) is the thickness of the GP-type absorption layer and \( v_{\text{drift}} \) is the drift velocity of the carrier. The drift velocity can be written as

\[ v_{\text{drift}} = \mu E = \mu V / d_{\text{GP}} \]  

(4)

where \( \mu \) is the mobility, \( E \) is the electrical field, and \( V \) is the potential difference between the ends of the GP absorption layer. Substituting Eq. 4 in Eq. 3, one can get

\[ d_{\text{GP}} \leq \sqrt{\mu \cdot V \cdot \tau_h} \]  

(5)

Taking the ratio of \( d_{\text{GP}} \) to \( d_{\text{flat}} \) from Eqs. 2 and 5,

\[ \frac{d_{\text{GP}}}{d_{\text{flat}}} = \sqrt{\frac{eV}{kT}} \]  

(6)

can be derived. Using appropriate values, the GP type can have a thicker absorption layer than the flat type by a factor of 4.4. Enhancement of heat dispersion due to the use of the thicker absorption layer is promising for making LD operation less temperature sensitive.

We can estimate the absolute value of the thickness of the GP-type absorption layer by using Eq. 5. The lifetime of \( \tau_h \) changes from \( 10^{-9} \) to \( 10^{-4} \) second, depending on the impurity density. Here we take the smallest value of \( 10^{-9} \) s for a conservative estimate. Assuming \( \mu = 100 \) cm\(^2\)/Vs (for AlAs), and \( V = 0.5 \) V, the \( d_{\text{GP}} \) should be less than 2.2 \( \mu \)m. This is comparable to the micrometer-level thickness needed for efficient absorption, which can easily be derived from the absorption coefficient of \( 10^4 \) cm\(^{-1} \). This means that the micrometer-level absorption layer enables the realization of both efficient absorption and carrier transfer to the active layer.

In addition to the use of the drift process in the GP-type SPLD, the diffusion effect may be enhanced by controlling the spatial profile of the graded potential. The hole current \( J_h \) due to diffusion is defined as

\[ J_h = -e \cdot D_h \cdot \frac{\partial p}{\partial d} \]  

(7)

where \( p \) is the hole density at spatial position \( d \). Since the diffusion coefficient of \( D_h \) is determined by the material, a larger hole density gradient can enhance the current. The larger gradient requires a larger number of carriers in the part of the absorption layer far from the active layer, compared with that in the near part. This situation may be produced by controlling carrier-production distribution, using a non-linear graded potential structure. The combination of the solar light spectrum as input, and wavelength-dependent absorption coefficients for \( \text{Al}_x\text{Ga}_{1-x}\text{As} \) in the various mole fraction of \( x \) will determine the feasibility. Since the GP controls the carrier-production distribution for diffusion enhancement, this non-linear-GP-type SPLD can be called a functionally graded material.

4. Concluding Remarks

A solar-pumped laser diode (SPLD) using graded-type concept has been proposed. The potential structure of the laser device was discussed, including the absorption and transfer of carriers into the active layer that will emit laser light. The use of a non-linear graded potential was mentioned for the first time as a possibility to enhance performance.

References

