NASA-TM-75869 19810012338

NASA TECHNICAL MEMORANDUM   NASA TM-75869

SEMICONDUCTOR DEVICES FOR OPTICAL COMMUNICATION IN 1 μm
                    BAND OF WAVELENGTH

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON D.C. 20546   NOVEMBER 1980

1. Report No. NASA TM-75869	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Semiconductor Devices for Optical Communication in 1 µm Band of Wavelength		5. Report Date November 1980
		6. Performing Organization Code
7. Author(s) Y. Suematsu, K. Iga		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASW-3198
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A summary is given of research on semiconductor devices for the long wavelength band used in optical communications. It is concluded that to utilize the advantages of this band, it is necessary to have a large scale multiple wavelength communication, along with optical cumulative circuits and optical exchangers.

17. Key Words (Selected by Author(s))	18. Distribution Statement Unclassified – Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 34	22.

SEMICONDUCTOR DEVICES FOR OPTICAL COMMUNICATION IN 1 μm BAND OF WAVELENGTH

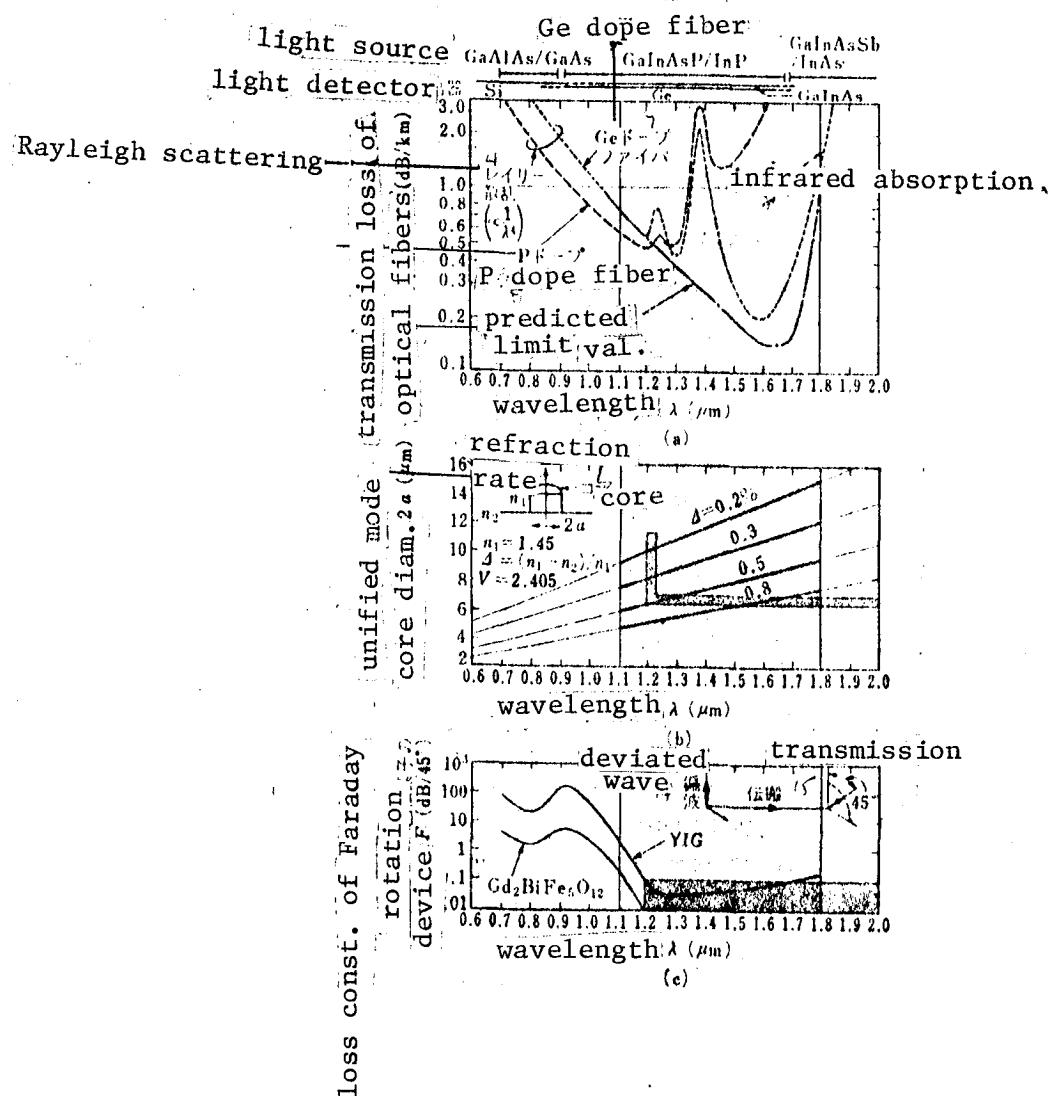## Yosuharu Suematsu and Kenichi Iga

1.   Introduction

In the research on fiber optic communication which is achieving a remarkable degree of development in the recent years, systems for practical use have been developed for 0.8 μm band of wavelength, thus completing the so-called first generation. Now, the focus of research and development is about to start moving to the so-called long wavelength band with wavelengths of 1-1.8 μm, where loss of optic fiber is extremely small, which might be regarded as the second generation of fiber optic communication. The inception of this optical communication in the long wavelength band is the prediction that if the absorption by water is removed from silica fibers, the greater degree of reduction in loss could be achieved for longer wavelengths, based on determinations of optic fiber losses over the long wave length zone by Maurer and others [1], followed by the development of manufacturing of silica fibers by the CVD method [2]. At the same time, research on new semiconductor material with the width of exclusion zone of 1 μm has also been started [3-4]. Subsequently, in 1976, cooperative research by Japan Telecommunication Corporation and Fujikura Densen, Co., developed a revolutionary fiber with transmission loss of 0.5dB/Km at the wave length of 1.3 μm [15], which resulted in worldwide attention attracted to the optical communication devices of the second generation, such as the light source and

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* Numbers in the margin indicate pagination in the foreign text.

optical wave detector for this wavelength band.

The characteristics of the second generation long wave-length optical communication device have been described in reference [16], but we would like to summarize them in our own way of thinking: (1) optical transmission with extremely small loss is possible, so that exceedingly long relay distance could be attained. The transmission loss of optical fibers is shown in Figure 1 (a). With a wavelength of 1.6 μm, a loss of 0.2dB/Km was achieved at the end of 1978 (Ibaraki Communication Laboratory, Japan Telecommunication Corporation [17].; (2) because of the small loss of 1dB/Km or less over a wide range of wavelengths from 1.1-1.8 μm, the multiplex wavelength system [18] in which a large number of different wavelengths is transmitted on a single fiber could be utilized, so that the high frequency of optical wave frequency could be used effectively; (3) as shown in Figure 1, the core diameter that fulfills the condition for unitary mode transmission of optical fibers could be taken at relatively large values; (4) the Rayleigh scattering which is one of the factors in optical loss in laser and optical circuits becomes smaller in the long wavelength zone, in proportion to λ^{-4}; (5) Garnet type materials for optical isolator become transparent above 1.2 μm, which was not easily achieved in the first generation (1). (In Figure 1 (c), optical absorptive losses against wave deviation at 45° rotation, necessary when materials such as YIG are used in an isolator [20], are shown as new performance index). Lastly, just to make an additional point, (6) over this range of wave lengths, the material scatter, which acts as one of the factors in limiting the range of transmission band of optical fibers, could be held within ± 3ps/Km (distance). Å (width of wavelength) [21].

Furthermore, when wavelength increases, as could be seen from Figure 1 (a), transmission loss increases due to the effects

light source

light detector

Ge dope fiber

GaAlAs/GaAs   GaInAsP/InP   GaInAsSb/InAs

GaInAs

Rayleigh scattering

transmission loss of optical fibers (dB/km)

3.0
2.0

1.0
0.8
0.6
0.5
0.4
0.3

0.2

0.1

Ge fiber

infrared absorption

P dope fiber

predicted limit val.

0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0

wavelength λ (μm)

(a)

unified mode core diam. 2a (μm)

refraction rate

core

16
14
12
10
8
6
4
2

n_1
n_2
$2a$
$n_1 = 1.45$
$\Delta = (n_1 - n_2)/n_1$
$V = 2.405$

$\Delta = 0.2\%$
0.3
0.5
0.8

0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0

wavelength λ (μm)

(b)

loss const. of Faraday rotation device F (dB/45°)

deviated wave

transmission

10^3
100
10
1
.1
.01

45

YIG

$Gd_2BiFe_5O_{12}$

0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0

wavelength λ (μm)

(c)

(a) Transmission loss of optical fibers,
(b) Fiber core diameter of unified mode, 2a,
(c) Loss constant to deviated wave surface
    rotation of 45° Faraday rotation device.

Figure 1.   Characteristics of optical devices in long
            wavelength zone

specific infrared absorption due to molecular vibration of
SiO_2 and GeO_2, which is a dopant. However, materials such as
CsI which become transparent with longer wave lengths (0.01dB/
Km or less), are being studied as optical guides for medical
use [22]. Thus, optical communication in longer wavelength
areas such as $\lambda = 2-10$ μm, utilizing the advantages as noted in
(3) and (4) above, is not impossible. However, with an increase
in wavelength, the energy of photon hf (h: Planck's constant,
f: frequency) decreases. At the wave length of 10 μm, it is
0.12eV. On the other hand, thermal energy kT (k: Boltzmann
constant, T: absolute temperature) is 0.03eV at 70°C, which is
a high temperature in the field of communication, so that it
becomes not negligible in comparison with the photon energy of
long wavelengths. Thus, effects appear on optical detectors
and on thermal characteristics of lasers. Accordingly, lasers
and optical detectors based on principles different from those
for the optical devices which were effective in the second and
third generations become necessary, so that the area of
$\lambda > 2$ μm could be termed optical communication of the fourth
generation.

In this article, semiconductor devices for the 1-1.8 μm
band are discussed, but one should not forget the accumulation
of basic research which led to the recognition of the excellent
advantages of this wavelength band.

2. Lattice-adjusted four-dimensional semiconductor crystals.

2.1. Crystal formation and width of exclusion zone.

No two-dimensional semiconductor crystals with the width
of exclusion zone corresponding to the 1 μm wave length band
noted above, are available, so that it is necessary to use
three or four dimensional crystals. However, for optical

semiconductor devices with high electric current density ($\sim$5KA/cm^2 μm) and high optical power output ($\sim$1 mW/μm^2) activation such as semiconductor lasers and LEDs, and photodiodes for low noise optical detection, it is important to carry out adjustment of lattice constants between the base plate crystal used for crystal growth and the four-dimensional crystals that serve as the activated layers. For example, the lattice maladjustment between Ga As and $Ga_{1-x}Al_xAs$ (x=0.3-0.5) used in the GaAs system of semiconductor lasers is around 0.03-0.05%. On the other hand, four-dimensional mixed crystals consisting of four elements could alter the width of the exclusion zone greatly while perfect lattice adjustment with two dimensional crystals used as the basal plate is maintained. In Figure 2, the relationships between various two-dimensional crystals with lattice constants of four-dimensional crystals they form, and width of the exclusion zone are shown. For example, in $Ga_xIn_{1-x}As_yP_{1-y}$ with InP(a=5.8696Å) as the basal plate, changing of compositions along the abscissa enables changing of widths of the exclusion zone over the range of $0.75 \leq E_g \leq 1.35$eV. As the mixed crystals corresponding to the so-called 1 μm band, the following could be considered [23]. Substances in the parentheses represent basal plates. With these, crystal growth is possible with lattice maladjustment of $\pm$ 0.03% or below.

(1) $Ga_xIn_{1-x}As_yP_{1-y}$(InP) : $0.92 < \lambda_g < 1.67\,\mu$m

(2) $Ga_{1-x}Al_xAs_ySb_{1-y}$(GaSb) : $0.8 < \lambda_g < 1.7\,\mu$m

(3) $Ga_xIn_{1-x}As_ySb_{1-y}$(InAs) : $1.68 < \lambda_g < 2\,\mu$m

(4) $Ga_xIn_{1-x}As_ySb_{1-y}$(GaSb) : $1.8 < \lambda_g < 2\,\mu$m

For the past 3 years, hetero-combination of the first system, that is $Ga_xIn_{1-x}As_yP_{1-y}$ with InP as the basal plate, and InP have been studied mainly because of the excellence in crystal formation for use as the material for lasers and photodiodes.
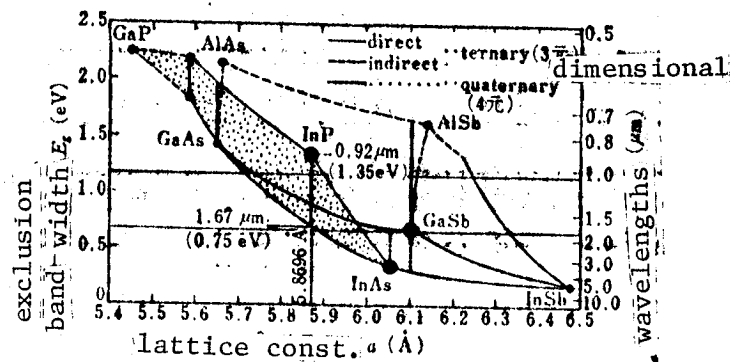
Figure 2.   Lattice constants and exclusion band widths of
III-V group compound semiconductors

Thus, the conditions of crystal growth of this system   /29
are summarized below.

2.2   Crystal growth in GaInAsP/InP.

The cross sectional structure of a wafer for a semicon-
ductor laser with GaInAsP as the laser activation layer and
InP as the clad layer, is as follows (also, see Figure 6):
First, n-type InP is placed over the InP basal plate, over which
GaInAsP without doping, and the p-type InP layer as the clad
layer are superimposed [24].   At times, a p-type GaInAsP layer
is placed over as a cap layer, to form excellent ohmic electrodes
[25].   For measurements of the cross section of the activation
layer, the cleaned cross section is stain-etched with a mixture
solution of $K_3Fe(OH)_6$ and KOH, and the surface is measured
by SEM.

In order to obtain the multilayered thin film wafer as

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described above, various methods such as vapor phase epitaxy, liquid phase epitaxy, and molecular beam epitaxy have been tried. Of these, the liquid phase epitaxy method of crystal growth is most popularly used, and renders high quality wafers for lasers. Thus, this method is summarized here. To grow a multilayered thin film of $Ga_x In_{1-x} As_y P_{1-y}$ by the liquid phase epitaxy method, solid phase extraction from a supercooled solution using a slide board, similar to a GaAlAs laser, is utilized. Usually, In is used as the solvent, and GaAs, InAs, and InP as the sources for Ga, As, and P. The deviation extraction coefficient $k_n \equiv 2x_N^S / x_N^l$ is used as a parameter to show the proportions of respective components of the solid phase four dimensional crystal x_N^S (N-Ga, In, As, P) extracted from the liquid phase components $x_N l$ in the solvent. With specific components $x = X_{Ga}s$, $y = X_{As}s$, k_N takes different values. In order to understand the conditions for crystal growth, it is necessary to construct phase diagrams centered around knowing k_N. Several studies have been carried out over the past 2-3 years in this direction [6, 9, 24-33], elucidating the conditions for crystal growth of GaInAsP. From these, experimentally obtained liquid phase components $x_N l$, with supercooling method with temperature of starting crystal growth of 630-650°, are shown in Figure 3. From the figure, the amount of source crystals to be dissolved in the In solution could be determined. The studies cited here are recent ones based on systematic experiments, but it should be remembered that in the early, pioneering studies, a great deal of work was expended in determining the amounts of source crystals to be dissolved. As could be seen from the figure, some differences are noted due to temperatures for starting of crystal growth, and method of cooling. Scattering seen in similar systematic studies may be due to errors in weighing of source crystals as well as error in measuring of solid phase component ratio.
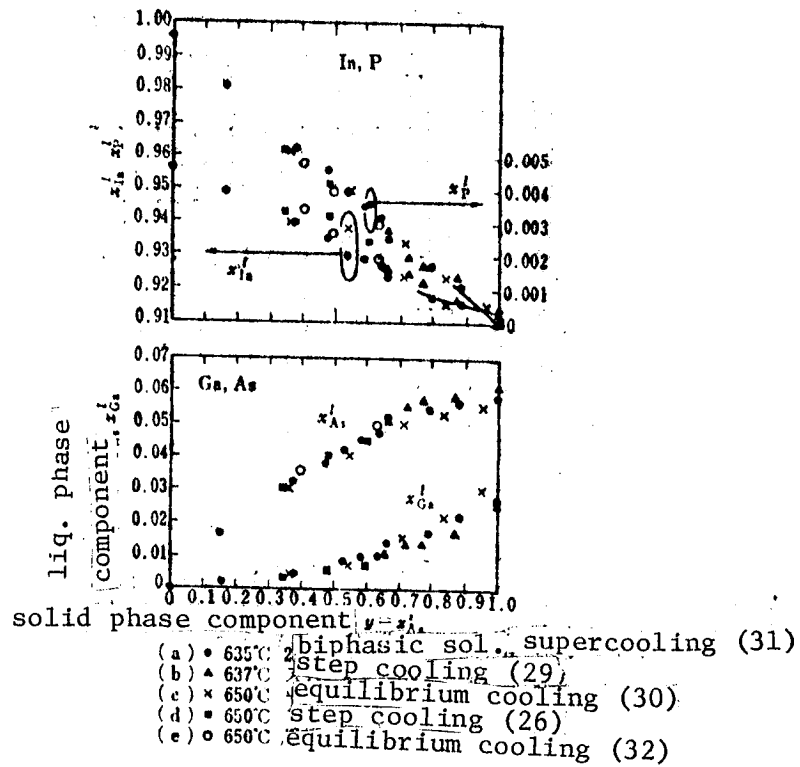
Figure 3.   Amounts of liquid phase components x_n^l (N=Ga, In, As, P) against As solid phase components of $Ga_xIn_{1-x}As_yP_{1-y}$

(a)   635°C   biphasic solution supercooling (31)
(b)   637°C   step cooling (29)
(c)   650°C   equilibrium cooling (30)
(d)   650°C   step cooling (26)
(e)   650°C   equilibrium cooling (32)

Based on the liquid phase components as described above, GaInAsP crystals with good lattice adjustment with the InP basal plate should grow, but since there are some differences in absolute temperatures of the basal plate and solution caused by different furnaces used, to achieve complete lattice adjustment and select the oscillating wavelength exactly as designed, fine tuning is carried out by slightly changing concentrations of Ga [34] or As [35]. Theoretically, it is possible to make Δa be zero. The separation capability of the x-ray diffraction meter in general use is about $\pm 0.03\%$, so that the degree of

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adjustability has the limitation of this degree. When the
lattice of a four-dimensional crystal is not adjusted with that
of InP, distortion of the lattice is seen mainly in the direction
perpendicular to the plane of the basal plate, and virtually no
changes are seen in the direction parallel to that plane [34].
Thus, it is considered that if the direction of the plane chosen
for x-ray diffraction is taken in the direction perpendicular
to the basal plate such as (400), the degree of maladjustment
could be measured quite well.

In terms of the direction of the plane of the InP basal
plate used in crystal growth, in the early phase of research,
the use of the (100) plane resulted in the formation of small
holes of 1 μm size, and poor reproducibility, so that the (111)B
plane has mainly been used. However, since Hsieh [36], and
Itaya and the authors [37] successfully constructed semiconduct-
or lasers of equally good performance level, using the (100)
plane as the basal plate, the (100) plane is now being used
frequently. The advantages of the (100) plane include the ease
of cleavage, ease of crystal growth in terms of selective crystal
growth, etching and lattice adjustment, as well as the fact   /30
that technology accumulated by GaAs method could be utilized
for forming into various shapes by etching.

Also, the relationship between the solid phase component
ratios $x=X_{Ga}$s and $y=X_{As}$s of four=dimensional crystals formed
with lattice adjustment, and width of the exclusion band E_g are
extremely important in practical use. These are determined by
substituting experimental values into Vegard's law. Using
a recent report [38], the relationship between x and y in condi-
tion of lattice adjustment could be expressed as

$$x=\frac{0.466\,y}{1.03-0.03\,y} \quad (0 \leq x \leq 1)$$ (2)

and the width of the exclusion band E_g could be given by the

solid phase composition ratio y of As, thus:

$$E_g(y) = 1.35 - 0.72\,y + 0.12\,y^2 \quad (eV)$$ (3)

In Figure 4, E_g or the corresponding wavelength x_g, are shown.

3. Semiconductor lasers

For semiconductor lasers of 1-1.7 μm band, the structure and characteristics, mainly centered on the GaInAsP/InP system, are summarized.

3.1. Area of oscillating wavelength and threshold electric current

The width of the exclusion band of $Ga_x\,In_{1-x}As_y\,P_{1-y}$ could be expressed as an approximation by the equation (3). The range of possible wavelengths includes $0.92 < \lambda_g < 1.67$μm. A semiconductor laser of double hetero structure with InP as the clad layer, as shown in Figure 6, has been materialized over the range of wavelengths $1.1 < \lambda < 1.67$ μm.

In Figure 5, threshold electric current density per unit activated layers J_{th}/d of the $Ga_x\,In_{1-x}As_y\,P_{1-y}$/InP laser is shown. With liquid phase epitaxy, about $4.5KA/cm^2$ μm have been achieved for $1.1 < \lambda < 1.55$ μm [24, 25, 33, 35, 39, 41]. For the maximum wavelengths of x=0.466, y=1, with the liquid phase method, the density is about $12kA/cm^2$ μm [42] for the GaInAsP/ GaInAs/InP structure, and $8kA/cm^2$ μm [33] for the InP/GaInAsp/ GaInAs/InP structure. However, with the molecular beam method, the value is lowered to the neighborhood of $5kA/cm^2$ μm [43]. Also, for lasers of $1.2 < \lambda < 1.4$ μm made by gaseous phase epitaxy, about $6kA/cm^2$ μm has been achieved [38], demonstrating the high quality crystals equivalent to those made by the liquid phase method. Accordingly, it appears possible to manufacture
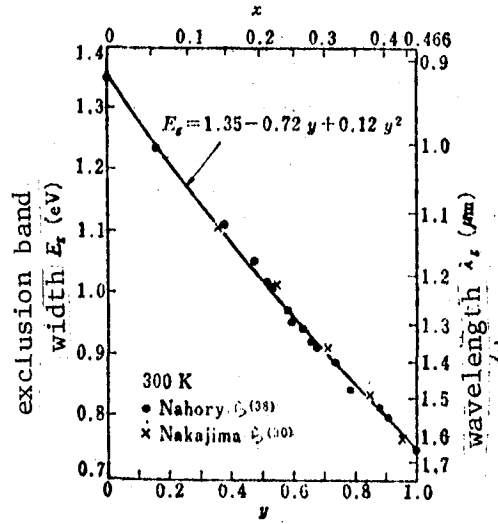
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Figure 4. Width of exclusion band E_g against
solid phase component ration $x = X_{Ga}s$, $y = X_{As}s$
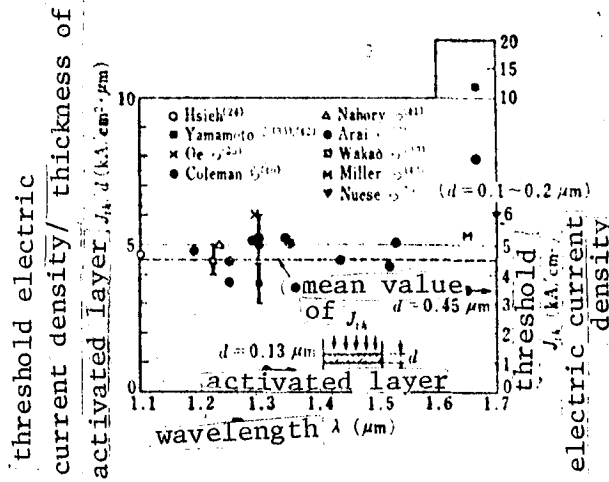

Figure 5. Threshold electric current density J_{th}/d
that corresponds to the thickness of unit activated
layer of GaInAsP/InP laser. In terms of carrier
concentration, 5kA/cm^2 μm corresponds to about 3
x 10^{16}/cm^3.

lasers with low threshold electric current over almost all areas of components of this four-dimensional material.

Variations of threshold electric current density J_{th} in terms of thickness of the activated laser d have been studied [41, 45, 46]. At present, the minimum value is present in the neighborhood of d=0.1∿0.2 μm, with J_{th}=1 [45] ∿2kA/cm^2 [41]. A low value such as 0.78 kA/cm^2 for d=0.13 μm has been recorded. Usually, the activated layer is left without doping on purpose, but since Zn that diffuses fast is frequently used as a dopant in the p type InP layer of layer III, diffusion into the activated layer during crystal growth could sometimes occur, precluding normal hetero combination. Especially with a thin activated layer (less than 0.1 μm), the selection of Zn concentration in accordance with value of d could lead to the reduction of threshold electric current [45]. Cd has also been tried as a dopant [43].

It is desirable to minimize impurity concentrations in the activated layer. The reason for this is that the yield difference in the vertical mode increases, and hole burning becomes less likely to occur [47], making the single vertical mode /31 oscillation at the time of CW quite easy.

The index of refraction of GaInAsP for λ=1.3 μm is n=3.5 [48, 66], and that for InP is n=3.23 [49]. It follows that the difference in specific refraction index, which serves as an index for sealing-in effect of light, $\Delta=(n_1-n_2)/n_1=717\%$. This, in comparison to x=0.4 for $Ga_{1-x}Al_xAs/GaAs$, is quite large.

3.2. Structure of stripe lasers

With semiconductor lasers, it is customary to form a stripe type activated layer with 2-15 μm width, in order to achieve the stabilization of horizontal mode, the improvement of

linearity of the electric current to light power output characteristics, and the unification of vertical mode. Methods of construction of several types of stripe laser in the GaAs/GaAlAs laser have already been established [50]. Similar stripe construction has been tried for the GaInAsP/InP laser. Also, entirely new types have been proposed.

An example of an electrode stripe, which is one of the frequently used stripe constructions, is shown in Figure 6. The p$^+$ layer of GaInAsP [25] is often provided in order to improve ohmic contact with the anode. Examples of other stripe-type structures are shown in Figure 7. Of these, (a)∿(f) possess the optical wave conduction function in the horizontal direction as well by difference in refractory rates, so that the horizontal mode is stable when electric current is increased and vertical mode is also highly likely to be unified. Figure 8 shows the spectrum of the electrode stripe type GaInAsP/InP laser and examples of measurements of electric current versus power output [54].

Typical action parameters of the GaInAsP/InP stripe lasers include: voltage = 0.9V, electric current 100∿200mA, resistance 1-2Ω, power output = several mW. Heretofore, experiments have been performed mainly with the system of λ=1.3 μm, but approximately similar characteristics could be expected for 1.1∿1.55 μm. For the 1.6 μm band, further studies are needed for areas such as improvements in methods of crystal growth.

3.3. Thermal characteristics

A unique characteristic of semiconductor lasers is that with an increase in the electric current entering, a threshold value is reached as shown in Figure 8(b). For higher electric current, efficiency of luminescence becomes exceedingly great. If threshold electric current density at temperatures T' and T
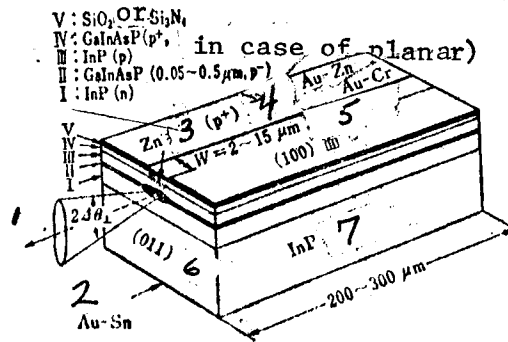
Figure 6. Commonly used electrode stripe or planar
stripe type GaInAsP/In laser. (In practical use, this
is frequently mounted with the anode facing downward).

1 - light; 2 - cathode; 3 - diffusion; 4 - anode; 5- stripe;
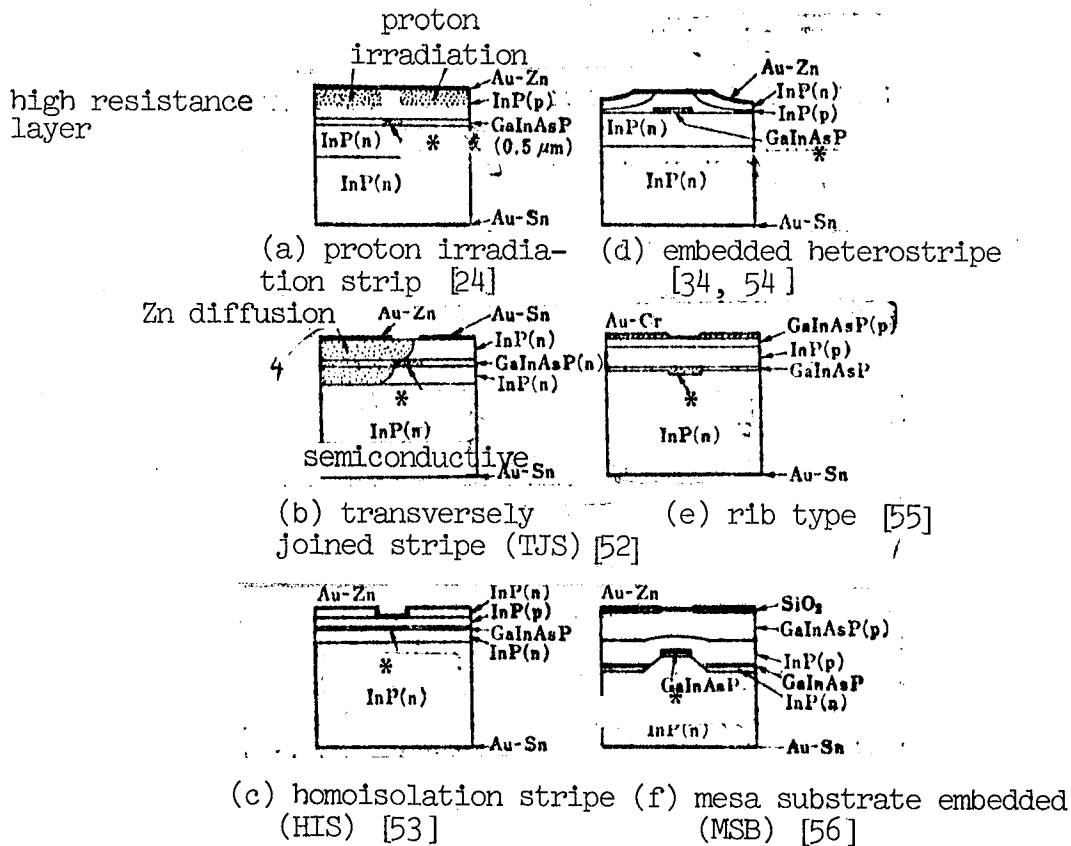6 - surface; 7 - basal plate

(a) proton irradia-
tion strip [24]

(b) transversely
joined stripe (TJS) [52]

(c) homoisolation stripe
(HIS) [53]

(d) embedded heterostripe
[34, 54]

(e) rib type [55]

(f) mesa substrate embedded
(MSB) [56]

Figure 7. Examples of Cross Sectional Structure of
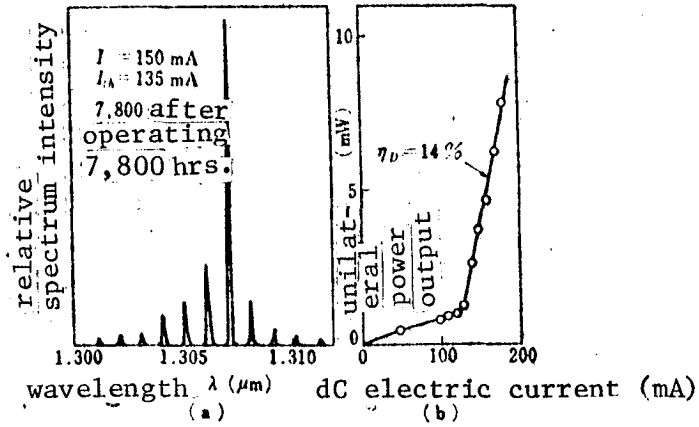Stripe Type GaInAsP/InP Lasers
* activated area

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Figure 8. Examples of (a) spectrum and (b) electric
current-optical power output characteristics of
GaInAsP/InP laser [51]

are designated respectively as J_{th} (T') and J_{th} (t), then their

relationship could be expressed as: /32

$$J_{th}(T)=J_{th}(T')\exp[(T-T')/T_0] \qquad (4)$$

Here, T_0 is the characteristic temperature, which is the tempera-
ture where J_{th} becomes e times as great when thermal elevation
T-T' is T_0.

There are two characterisitic experimental facts related
to the thermal characteristics of threshold values for GaInAsP/
InP lasers. The first is the rapid decrease in T_0 in the neigh-
borhood of room temperature [35, 57]. This is small, for
example, in comparison with 100-120K for GaAs/GaAlAs laser, and
improvements are needed for practical use. For high temperatures
above room temperature, leakage of electric current for the

hetero barrier is also possible, causing further increases in the threshold value. This effect has been measured by lasers with differing hetero barriers made by the vapor phase growth method. Figure 9 shows the ratio of the increase of threshold electric current density from 22°C of GaInAsP/InP lasers of differing oscillation wavelengths at 70°C [44]. It could be seen that the shorter the wavelength (that is, smaller hetero barrier), the poorer the characteristic temperature. However, at $\lambda > 1.3$ μm, the characteristic temperature could be converged to the level equal to that for a GaInAs three-dimensional laser.

On the other hand, the temperature fluctuation of oscillating wavelengths is about $3.5-4\overset{\circ}{A}/K$ [35, 53, 58], which is somewhat greater than that for GaAlAs lasers. However, with special constructions such as distribution Bragg reflection type (DBR), it becomes $0.7-0.8\overset{\circ}{A}/K$ [48].

3.4. Tests for durability of devices

The most important factor, above all else, for optical devices is their reliability. This newly developed material also has been studied for its durability from the inception. Fortunately, with GaInAsP/InP lasers, it was possible to find material with relatively long durability from the beginning of research, and it was felt that the material is of quite good quality. In addition, despite the high value of $10^4-10^8/cm^2$ ($\sim 10^3/cm^2$ with GaAlAs system) of the transposition density of InP crystals which are base plates, as etch pit density, devices with long durability have been made. This is appreciably different from the GaAlAs system. Continuous action at room temperature exceeding 10,000 hours with GaInAsP/InP lasers for 1.3 μm made with the (100) basal plate using the liquid phase method has been confirmed [51]. The spectrum shown in Figure 8 is one
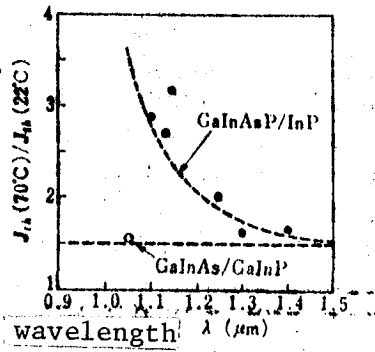
Figure 9.   Degree of elevation of threshold value of
            GaInAsP/InP laser, by vapor phase growth method[44]
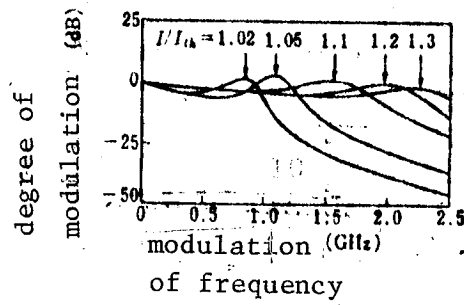

Figure 10.   Direct modulation characteristics of GaInAsP/InP
             laser (λ=1.3 μm) [68]
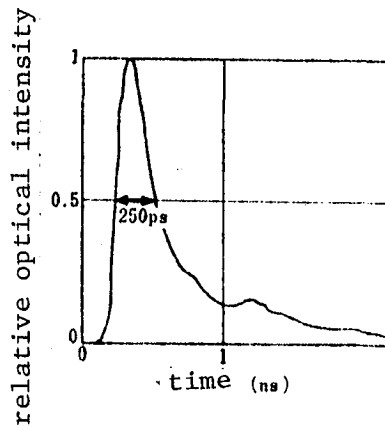

Figure 11.   Pulse modulation wave form of GaInAsP/InP
             (λ=1.3 μm) (detected by GeAPD [made by Fujitsu])

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after 7,800 hours. Also, with GaInAsP/InP lasers made by the
vapor phase method, continuous testing at room temperature
for 1,500 hours has been carried out [44], as well as high
temperature acceleration tests at 70°C.

In the future, research for devices with greater reliability
will continue through the elucidation of the mechanism of
deterioration which is thought to be somewhat different from
that of GaAlAs, development of InP basal plate with small
amount of transposition [59], improvement of electrodes, and
protection of mirror surfaces. Also, the material is thought to
have potential for such improvements.

3.5. Modulation and device characteristics

The length of recombination durability of the small number
of carriers injected to the activation layer, τ_s, is an important
parameter in determining the upper limit of the direct modulation
frequency, so that interest has been focused on these new four-
dimensional crystals from the inception. The attempted methods
for the determination of this parameter include: (1) the method
of measurement by elevations of pulse amplitude and threshold
value when narrow width pulse electric current is injected [37],
and (2) the method of measurement by the dependency of resonant
frequency on injected electric current [60, 61], and the method
by computing from the delay in oscillation time with pulse
excitation of electric current with fast standing up time [60,
61]. Compiling these results, it has been demonstrated that
τ_s=2-3ns for a laser of λ=1.2-1.3 μm, and the temperature depend-
ency of τ_s resembles that of a Ga As laser [53].

From the foregoing, it could be expected that direct modula-
tion to several GHz is possible with GaInAsP/InP lasers, similar
to Ga As lasers [60], and actual experiments on high speed pulse

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modulation [62] and measurements of frequency dependency on the degree of modulation [63] have been carried out. Figure 10 shows the degree of modulation when a laser with $\lambda=1.3$ μm is sine wave modulated. It shows the band area of over 2GHz for $I/I_{th}=1.3$, confirming the prediction from the value of τ_s. /33 Figure 11 is an example of the optical wave form when pulse modulation is carried out, showing that pulse amplitude of around 250ps is obtained.

As has been shown in Figure 6, the expansion of the light beam of a semiconductor laser is great in the direction perpendicular to the activated layer. This angle of expansion 2 $\Delta\theta$ is inversely proportional to the spot size of the resonant mode, so that by making the thickness of the activated layer exceedingly small, the spot size could be increased, and $\Delta\theta$ decreased. When d=0.05μm, about 23° is obtained [45], and even when d=0.13 μm, it is about 40°, which is equal to or less than for GaAs laser.

3.6. Development of new methods of manufacturing, material and models

For the method of manufacturing wafers for GaInAsP/InP lasers, the liquid phase expitaxy noted above is being firmly established with the completion of phase diagram almost attained. With wavelength band of 1.1–1.15 μm, wafers with threshold electric current density of 4.5 A/cm^2 μm could be constructed. The minimal threshold value is about 1KA/cm^2 for thickness of activated layer d=0.1-0.2 μm. On the other hand, basic research on construction of wafers by vapor phase epitaxy has been carried out, and at the International Convention on Semiconductor Lasers at the end of October, 1978, the first report of successful oscillation with a GaInAsP/InP laser was given, according to which J_{th}=7kA/ cm^2 μm or thereabouts, thus demonstrating wafers comparable to

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those made by the liquid phase method [44]. Since large size wafers for mass production could be constructed, and good control of film thickness for uses such as optical cumulative circuits could be attained, this is an exceedingly noteworthy method of production.

With $Ga_xIn_{1-x}As_yP_{1-y}$, if y=1, then GaInAs that corresponds to the maximum wavelength of $\lambda=1.65$ μm could be obtained. This is a three-dimensional crystal without containing P. When InP is grown on it for the clad layer, melt back develops, making crystal growth difficult. This has also been tried with the liquid phase method [33,42], with threshold electric current density of around $8kA/cm^2$ μm. However, with molecular beam epitaxy, the possibility of constructing wafers with $5kA/cm^2$ μm has been demonstrated [43]; aside from the practicability of this method of construction, it is noteworthy that lasers of fairly uniform performance level could be constructed for the entire wavelength of $Ga_xIn_{1-x}As_yP$.

As another material, GaAlAsSb/GaSb lasers with low threshold values have been reported. As noted previously, with $Ga_{1-x}Al_xAs_ySb_{1-y}$, luminescence is possible for the range of $0.8<\lambda_g<1.7$ μm. However, recently those with low threshold values of electric current density of $1kA/cm^2$ or less and range of 1.25 – 1.4 μm have been constructed [64]; also, a $Ga_xIn_{1-x}As_ySb_{1-y}/$ GaSb (basal plate GaSb) laser has been constructed, obtaining $\lambda=1.9$ μm, $J_{th}=900A/cm^2$ at 77K [65].

For construction aimed at mode stabilization, various types of embedded stripe construction as shown in Figure 7 have been proposed and tested, and it is likely that the development of lasers with stable horizontal modes, with wave conduction capability by different rates of refraction, would proceed. Also, as a method of construction aimed at the unification and stabilization of the vertical mode, a distribution Bragg reflector (DBR) laser that utilizes the primary diffractive lattice has been constructed on a trial basis [66], with which detailed

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studies on thermal characteristics have been carried out.
The optical cumulative circuit with InP as the basal plate is
considered by the authors to increase its importance in optical
circuit technology of the future.   To serve as a basis of this
technique, studies on chemical etching methods and on identifica-
tion of (011) and (01$\bar{1}$) directions with (100) InP basal plate
have been carried out.

4.   Luminescent diodes

    Development of luminescent diodes (LED) of 1 μm band has
been started since around 1977.   As with semiconductor lasers,
many of these diodes have the double hetero structure of Ga_xIn_{1-x}
As_yP_{1-y}/InP [29, 69, 72].   The type of wafer is basically similar
to that for lasers, as shown in Figure 6.   Figure 12 shows an
example of the structure of a plane luminescent type GaInAsP/
InP LED.   Since the InP basal plate is transparent for the lumin-
escent wavelength, it could be used as a window without modifica-
tion.   Frequently the activated layer in these diodes is not
covered with doping on purpose.   Power output is 1 [70] - 3mW
[71], external quantum efficiency is 1 [70] -3 [71]%.   Diodes   /34
with a wavelength band of 1.1 [68] - 1.5 μm [29] have been
constructed, and half-value widths of the luminescent spectra
Δλ are about 1,000-1,200Å.   The relative value Δλ/λ=0.07-0.08
is appreciably greater than 0.04-0.05 for GaAs LED.   Modulation
characteristics and combination with optical fibers have also
been studied, and the cutoff frequency has been determined to
be 60-70MHz [69].   A method to make the power output window into
a monolithic, convex lens shape has also been proposed [72].

5.   Optical detector

    The sensitivity of the Si photodiode used in the 0.85 μm
wave length band deteriorates markedly for wavelengths greater

than 1 µm. It is inevitable, theoretically as well, that in the longer wavelength band, effects of noise become greater. Heretofore, a Ge photodiode has been used as the optical detector corresponding to this wave length band, but there are problems of dark electric current and loud excessive noise, so that three and four-dimensional crystals have begun to be studied as photodiode material with low noise and fast height elevation close to 50 ps [73].

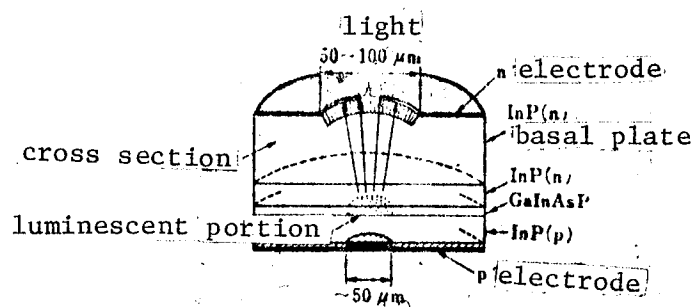light
50--100 µm
n electrode
InP(n)
basal plate
cross section
InP(n)
GaInAsP
luminescent portion
InP(p)
p electrode
~50 µm
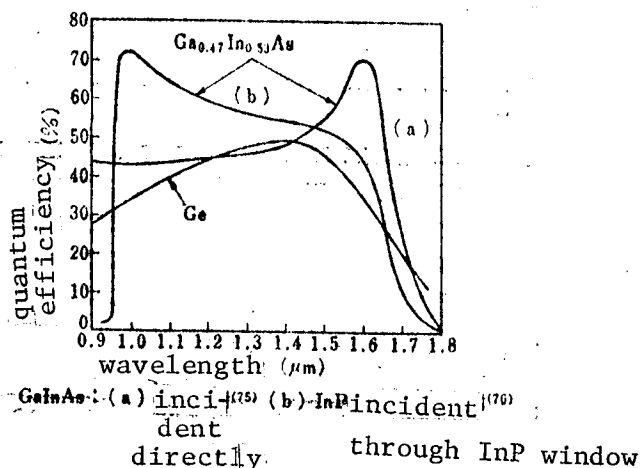
Figure 12. Example of construction of GaInAsP/ InP luminescent diode.

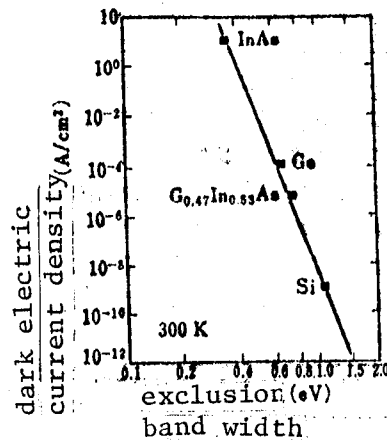Figure 13. Sensitivity of photodiode for 1 µm band

Figure 14. Measured values of dark electric
current density of photodiode .

Figure 13 shows wavelength sensitivity of photodiodes
made of Ge [74] and $Ga_{0.47}$ $In_{0.53}$ As [75, 76]. The sensitivity
of Ge is at around 1.5 μm, and avalanche photodiodes (APD) and
P-i-n construction photodiodes have been manufactured for
practical use. However, as shown in Figure 14, dark electric
current is 10^{-4} (A/cm^2), which is exceedingly greater than 2.5
x 10^{-9}(A/cm^2) for Si [75]. Also, since ionization coefficients
for electrons and positive hole are approximately equal, excess
noise at the time of avalanche amplification is great.

Four dimension crystals used in lasers as well, such as
$Ga_xIn_{1-x}As_yP_{1-y}$ and three dimension crystals $Ga_{0.47}$ $In_{0.53}$
with y=1, have been studies as the material for optical detectors
[73, 75-82]. Figure 13 shows quantum efficiency of a $Ga_{0.47}$
$In_{0.53}$ As photodiode, which has sensitivity to the largest wave-
length, among all the materials noted above. There is a report
that with this material, dark electric current could be reduced
to around 4-7 x 10^{-6} (A/cm^2)[75], appreciably such than that for
Ge. Also, it has been said that the ionization coefficients

at the time of avalanche amplification are greater for electrons than for positive holes [77]. If four-dimensional crystals with $\chi < 0.46$ are used, the width of the exclusion band increases and the maximum sensitivity moves to the short wave side [76].

Research on optical detectors for larger wavelengths, especially on APD, has just begun. It appears that GaInAs becomes low noise, but there are still some problems such as large transposition density of InP used for the basal plate.

At high speed, effects of dark electric current are small. With 32M bit/s PCM and when dark electric current is 100 nA, the deterioration of reception electric power of GeAPD is 4.5dB [16], so that requirements are somewhat less rigorous for the optical wave detector with high speed PCM. Ge has a long history in crystallization and economical potentials, so that it is being re-evaluated as a photodiode for long-wave optical detectors suitable for practical use. At least Ge photodiode could be used in the optical detector for longer wavelengths. Also, high performance detectors appear to be possible by the use of new materials such as GaInAs. Thus, the future for the optical detector for the 1 μm band is promising.

6.   Conclusion

In this commentary, we summarize the state of research thus far on semiconductor devices for the 1-1.8 μm band, the so-called long wavelength band, used in optical communication, which currently is attracting attention. In this wavelength band, because of the characteristics of optical fibers that serve as the route of transmission, semiconductor laser materials that serve as the light source were developed first, followed by the study of the optical detector. This sequence is the reverse of that for the 0.85 μm band. However, the exceedingly low transmission loss of 0.2 dB/km attracted a large number of researchers to make

efforts in the development of optical devices, so that at present, devices that could be considered as systems are being materialized. Thus, with GaInAsP/InP, long durability devices as semiconductor lasers with $\lambda=1.3$ μm have been constructed, and the same material may be able to be utilized for 1.1-1.67 μm. (After the completion of this text and while waiting for printing, CW operation at room temperature of a 1.5-1.6 μm band laser has been achieved successfully by KDD, Telecommunication Corporation, and Tokyo Engineering University). On the other hand, it is inevitable that the optical detector becomes high noise, but this is not detrimental for optical transmission. Optical isolators for long wavelengths have been constructed [20], and long-distance transmission experiments over 10 km [83, 85] and 50 km [84] have been carried out; thus photo-communication of the second generation appears to be able to be established on appreciably good balance of devices.

However, in order to really utilize advantages of the long wavelength band, it is necessary to have a large-scale multiple wavelength communication, along with its requirements such as optical cumulative circuits and optical exchangers. When these are well studied, the dawn of the third generation of optical communication will become visible. Deep appreciation is extended to those who provided their valuable research findings.

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