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Group 85

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ABSTRACT

A new scheme is proposed for achieving photoemission from semiconductors at infrared wavelengths from about 1 μ to well beyond 10 μ. The device consists of a graded-energy gap p-type semiconductor with a low work function coating on the wide-gap side. Electrons, which are photoexcited from the valence to the conduction band by long wavelength radiation in the narrow gap region are drifted by an applied electric field into the wide-gap region from where they are emitted into vacuum. Graded-gap $Hg_{1-x}Cd_xTe$ is considered for a photoemitter covering wavelengths to about 12 μ and both $Ga_{1-x}In_xAs$ and $InAs_xP_{1-x}$ are proposed as possible alloys for 3 μ photoemission. Preliminary calculations made with available parameter values indicate that the scheme holds considerable promise. For the simplest case of a linearly graded gap and a constant conductance, expressions are derived for the length of the graded region required to minimize power dissipation and for the speed of response. A calculation is also made of the dark current which results from thermal generation in the narrow gap region in order to determine the operating temperature required for achieving a desired noise-equivalent power (P_N) at any wavelength. For an overall quantum-efficiency of 10% an estimated operating temperature of 50^{o}K is required for achieving a P_N of about 10^{-14} W/Hz$^{1/2}$ in a 12 μ detector; for a 3 μ detector this P_N value can be achieved at approximately 130^{o}K.

Accepted for the Air Force
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THE GRADED-GAP SEMICONDUCTOR PHOTOEMITTER

Introduction

Photoemissive radiation detectors have distinct advantages over other forms of detectors because they are very sensitive, fast and convenient for imaging.[1] By directly converting a photon signal to a signal of electrons in a vacuum it is possible to use a first-stage amplifier -- the photomultiplier which is very nearly noiseless with a high gain (typically 10^5) and a wide bandwidth (10^9 Hz). High detectivities have been achieved in some photoconductors and in photovoltaic detectors. However, sensitive photoconductors require long carrier life-times which pose a limitation to the speed of response. In high detectivity photodiodes the bandwidth is in turn limited by a resistance-capacitance time constant. The bandwidth of diodes can be increased by achieving avalanche multiplication gain so that a low resistance load can be used to reduce the RC constant. However, the avalanche multiplication process itself is inherently noisy and the diodes generally have a higher dark current than photomultiplier tubes.

In the area of imaging, photoemitters have an advantage in their simplicity. By suitably designed electron optics, it has been possible to convert the emission pattern on the cathode to an electron-induced visible image on a phosphor screen, thus avoiding the necessity for complex array structures.

So far, photoemissive cathodes have been made by coating metals and more recently some semiconductors with layers of low-work function materials, particularly Cs_2O. These are useful in the wavelength range from the ultraviolet to about 1 micron in the infrared. Some of the semiconductors so far used are the III-V compounds,[2] GaAs,[3] InP,[4] $InAs_xP_{1-x}$,[5] $In_{1-x}Ga_xAs$[6] and $GaAs_{1-x}P_x$.[7] The energy level diagram proposed for the cesiated semiconductor surfaces is shown in Fig. 1. Radiation whose photon energy is greater than the bandgap (E_g) of the semiconductor excites electrons from the valence band to the conduction band from where they tunnel through the Cs_2O layer and are emitted into the adjacent vacuum. For this to happen, the semiconductor bandgap (E_g) must be at least as large as the work function (W). In practice, for Cs_2O surfaces which have a work function of about 0.6 eV, the longest wavelength at which efficient photoemission (10%) has been achieved in the laboratory[2] at present is approximately 1 μ. The premium on achieving efficient photoemission at wavelengths longer than this clearly is very high. At present some of the promising high power laser sources for optical communications and optical radar are at the wavelengths 1.06 μ (Nd-YAG), 1.54 μ(Er-Glass), 2.6-2.9 μ(HF), 3.6-4.1 μ(DF), 5 μ(CO), and 10.6 μ(CO_2). In the 8-14 μ range a photoemitter would be particularly useful for detection and imaging of objects near room temperature whose blackbody radiation peaks near 10 μ.

Recent efforts in extending the wavelength range have been largely limited to achieving photoemission by cesiating III-V compounds with energy gaps somewhat smaller than 1.2 eV (wavelengths slightly longer than 1 μ).[2] In order to achieve emission at significantly longer wavelengths by reducing the energy gap of the semiconductor, it is clear from Fig. 1 that low work function coatings in which the vacuum level is closer to the Fermi level than in Cs_2O will be required. No such coatings are available at present.

Graded-Gap Scheme

To avoid the necessity for a lower work function surface coating we propose to use a "graded gap" semiconductor as shown in Fig. 2a. The p-type semiconductor at the cesiated surface has an energy gap E_2 such that the conduction band edge is above the vacuum level. To the left of this surface the gap gradually decreases to the value E_1. If we apply a sufficient voltage V across this semiconductor with the polarity shown in Fig. 2b, the bands are tilted, as indicated. The electrons which are photogenerated at E_1 are swept into the E_2 region from where they can be emitted into vacuum. The longest detectable wavelength in this structure is determined by the energy E_1.

Graded gap semiconductors have been obtained by varying the composition of alloys such as $Hg_{1-x}Cd_xTe$.[8,9] In this alloy the gap can be varied from the CdTe energy gap of 1.6 eV down to zero and hence the detectable wavelength, in principle, could extend to far infrared wavelengths. Due to various practical considerations a realistic initial goal could be to achieve photoemission out to approximately 12 μ(0.1 eV energy gap). The $Hg_{1-x}Cd_xTe$ alloy graded gap structures have been grown by vapor epitaxy and have been investigated as photo-

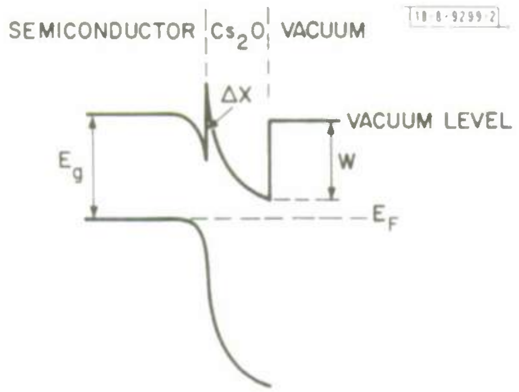

Fig. 1. Energy level diagram of a Cs_2O coated semiconductor photoemitter. W is the work function of the Cs_2O coating and ΔX is the difference in electron affinities of the semiconductor and the Cs_2O coating.

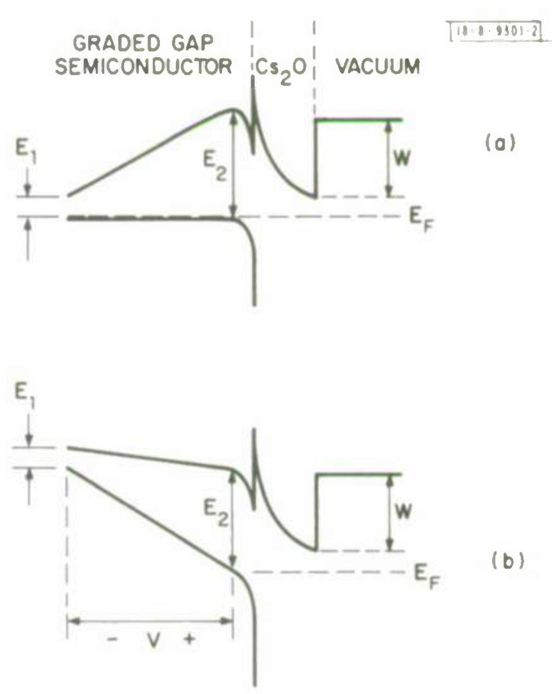

Fig. 2. Energy level diagram of a Cs_2O coated graded-gap semiconductor photoemitter with (a) no bias applied and (b) a bias voltage V applied to the graded gap region.

magnetic detectors. Among the advantages of this alloy is the nearly perfect match in the lattice constants of HgTe (6.429 Å) and CdTe (6.48 Å), which tends to avoid defects and stresses that occur with poorly matched lattice constants. Thus, measurements of the photomagnetic effect show that high mobility and lifetime values can be maintained throughout the graded gap region.[9] The high electron-to-hole mobility ratio is also favorable in this system because a low majority hole conductance means low power dissipation while a high minority electron mobility favors fast photoelectron transport across the graded gap region. A disadvantage to $Hg_{1-x}Cd_xTe$ at present is the lack of any work -- to our knowledge -- on photoemission from cesiated CdTe or wide gap $Hg_{1-x}Cd_xTe$. Also p-type CdTe or $Hg_{1-x}Cd_xTe$ with $x > 0.7$ with a concentration of 10^{19}-10^{20} cm^{-3} which may be necessary to avoid too wide a depletion region at the cesiated surface is not available at present.

Since efficient photoemission has been obtained from both $Ga_{1-x}In_xAs$ and $InAs_xP_{1-x}$ for small values of x (including zero) these alloys should also be considered, particularly since they also have a favorable electron-to-hole mobility ratio. The long wavelength limit in both alloys is approximately 3 μ, corresponding to the 0.4 eV energy gap of InAs. Such a detector would be useful for the 1.54 μ Er-doped Glass laser and for the HF laser near 3 μ. Crystals with graded alloy regions have readily been grown in a controlled way by vapor epitaxy in gas-flow systems.[10] However, no measurements of mobilities and lifetimes in the graded crystals are available at present. Unfortunately, the lattice constants in both these systems are not nearly as well matched as in $Hg_{1-x}Cd_xTe$. The constants for the binary compounds are

InAs	6.058 Å
InP	5.869 Å
GaAs	5.653 Å

Thus, for the $InAs_xP_{1-x}$ the mismatch is 3.1%, while for $Ga_{1-x}In_xAs$ it is 6.7%, compared to 0.31% in $Hg_{1-x}Cd_xTe$. The effects of this mismatch on carrier lifetimes and mobilities remain to be investigated.

<u>Electron Transport Across the Graded Gap Region</u>*

Carrier transport in graded gap structures has been considered in a number of articles.[9,11,12] A first necessary requirement for having a minority electron drift current from the E_1 to the E_2 region in Fig. 2 is that the applied voltage be sufficiently large so that

$$qV > E_2 - E_1$$

The resistivity of the p-type graded gap region must be sufficiently high to permit the application of such a voltage without excessive power dissipation. For the compounds considered this can be achieved with hole concentrations in the 10^{14} - 10^{15} cm^{-3} range. Since a heavier doping is required

*The simplified approach used in this section is justified in Appendix I.

at the cesiated surface in order to avoid an excessively wide surface depletion region, a thin p^+ region with a 10^{19} - 10^{20} cm^{-3} concentration will have to be formed at the E_2 surface by such means as diffusion or ion implantation. This p^+ layer will also make possible the application of a uniform voltage across the graded gap region at every point. In the graded gap region a lower limit to the hole concentration is set by the condition $\mu_h p >> \mu_e n$ which is required to avoid ambipolar effects. In practice this means that excessive freezeout of holes in the graded gap region should be avoided.

A second requirement is that the drift or diffusion length of electrons injected at E_1 is equal to or greater than the length of the graded gap region ℓ. The drift length L_d and the diffusion length L_n are given by

$$L_d = \mu_e \tau_e \mathcal{E}$$

and

$$L_n = \left(\frac{\mu_e kT \tau_e}{q}\right)^{1/2} ,$$

where μ_e and τ_e are the electron mobility and lifetime respectively and where $\mathcal{E}$ is the electron drift field. For $\mathcal{E} > \left(\frac{kT}{q\mu_e \tau_e}\right)^{1/2}$ the electron transport will be dominated by drift. In the situations of interest this occurs for fields greater than about 10 v/cm. The average drift field in the sample is $\mathcal{E} = \frac{V-\Delta V}{\ell}$ where V is the externally applied voltage and $\Delta V = \frac{E_2 - E_1}{q}$. This expresses the fact that sufficient voltage has to be applied to overcome the built-in field due to the difference of the two energy gaps (ΔV) before the electrons will experience a net force in the direction of E_2. Setting the maximum length ℓ_m equal to the drift length L_d (for a transmission-efficiency for the graded region η_t of e^{-1}) we have

$$\ell_m = [\mu_e \tau_e (V - \Delta V)]^{\frac{1}{2}} \tag{1}$$

and

$$V = \frac{\ell_m{}^2}{\mu_e \tau_e} + \Delta V \tag{2}$$

The power dissipated is given by

$$P = \frac{V^2}{R} = \frac{V^2 \sigma A}{\ell} \;:\; \text{or } P_A \equiv \frac{P}{A} = \frac{V^2 \sigma}{\ell} \tag{3}$$

As a first approximation we assume that the graded gap region has a constant conductivity (σ) determined only by majority carriers. If in addition we assume that the gap is linearly graded then the drift field $\mathcal{E}$ is constant over ℓ.

The dissipated power becomes

$$P_A = \frac{\sigma}{\ell_m} \left(\frac{\ell_m{}^2}{\mu_e \tau_e} + \Delta V \right)^2 \tag{4}$$

For a set of parameters μ_e, τ_e and ΔV we can choose ℓ_m in order to minimize the power dissipation. Setting $\frac{dP_A}{d\ell_m} = 0$ and solving for ℓ_m yields

$$\ell_m' = \left(\frac{\mu_e \tau_e \Delta V}{3}\right)^{\frac{1}{2}} \tag{5}$$

The power and the voltage then are given by

$$P_A' = \frac{\sigma (V')^2}{\ell_m'} = \frac{3.1\ \sigma \Delta V^{3/2}}{(\mu_e \tau_e)^{\frac{1}{2}}} \quad ; \tag{6}$$

$$V' = \frac{4}{3}\Delta V \tag{7}$$

Example 1:

For a $Hg_{1-x}Cd_xTe$ 12 μ detector we take $E_1 = 0.1$ eV and $E_2 = 1.3$ eV. We assume that 1.3 eV is a sufficiently large energy gap to produce efficient photoemission, since such photoemission (10% efficient) has been recently observed in Cs_2O - $InAs_xP_{1-x}$ photoemitters with an energy gap close to this value.[2]

Calculation of the dark current which is carried out farther on indicates that such an emitter may have to be cooled to a temperature somewhat lower than 77°K. For the estimates made here 77°K values will be used, however, because these are more available. In a graded gap p-type $Hg_{1-x}Cd_xTe$ structure at 77°K the following values have been measured for electrons at different energy gap values:[9]

x	E_g	$\mu_e(cm^2/Vsec)$	$\tau_e(sec)$	$\mu_e\tau_e(cm^2/V)$
0.20	0.1	$1.5x10^5$	$2.5x10^{-9}$	$3.75x10^{-4}$
0.23	0.2	$5.5x10^4$	$2x10^{-8}$	$11x10^{-4}$
0.70	1.0	$2.5x10^4$		

The mobility increases and the lifetime decreases with increased energy gap. Thus, the product $\mu_e\tau_e$ has only a relatively small variation with E_g. A somewhat conservative value of $4x10^{-4} cm^2/V$ will be assumed for $\mu_e\tau_e$ throughout the graded gap region. A hole mobility of about 10^2 $cm^2/Vsec$ has been measured[13] in p-type alloys with x near 0.20 for carrier concentrations above 10^{17} cm^{-3}. Higher hole mobilities can be expected at lower carrier concentrations; however, in the region where the gap becomes wider the mobility should be lower. A constant hole mobility of 10^2 will be assumed in this calculation. Since electron concentrations in n-type crystals of 10^{14} - 10^{15} cm^{-3} have been achieved[13] we expect that hole concentrations of about 10^{15} cm^{-3} should be within the reach of present technology. Hole freezeout to concentrations smaller than 10^{15} cm^{-3} have been observed at temperatures below 77^oK.[14] In summary, the following values will be used in the calculation:

$$E_1 = 0.1 \text{ eV}$$
$$E_2 = 1.3 \text{ eV}$$
$$\mu_e\tau_e = 4x10^{-4} \text{ cm}^2/V$$
$$\mu_h = 10^2 \text{ cm}^2/Vsec$$
$$p_o = 10^{15} \text{ cm}^{-3}$$

With these values we obtain

$$\Delta V = 1.2 \text{ V}$$

$$\sigma = 1.6\text{x}10^{-2} \text{ mho}$$

$$\ell_m' = 1.3\text{x}10^{-2} \text{ cm} = 130 \ \mu$$

$$V' = 1.6 \text{ V}$$

$$P_A' = 3.2 \text{ W/cm}^2 = 32 \text{ mW/mm}^2$$

For comparison, for $\ell_m = 10 \ \mu$

$$V \approx 1.2 \text{ V}$$

$$P_A = 23 \text{ W/cm}^2 = 230 \text{ mW/mm}^2 \quad ;$$

For $\ell_m = 1000 \ \mu$(1mm)

$$V = 26\text{V}$$

$$P_A = 110 \text{ W/cm}^2 = 1.1 \text{ W/mm}^2$$

<u>Example 2</u>

Since GaAs is a better developed and characterized material than InP the $Ga_{1-x}In_xAs$ alloy will be examined here rather than $InAs_xP_{1-x}$. However, the results obtained in this calculation may be considered an estimate for both alloy systems. For $Ga_{1-x}In_xAs$ we vary the energy gap from $E_2 = 1.3$ eV to $E_1 = 0.4$ eV (InAs), corresponding to a long wavelength limit of 3 μ. Epitaxially grown n-type GaAs crystals with carrier concentrations in the 10^{13}-10^{14} cm^{-3} range[15] and n-type InAs crystals with electron concentrations[16] of $4x10^{15}$ cm^{-3} have been obtained. By introducing a p-type impurity during the growth process, controlled compensation should be possible for achieving hole concentrations below 10^{15} cm^{-3}.

Values of lifetimes are not known for uniform $Ga_{1-x}In_xAs$ or for graded gap structures. Recently, lifetime measurements have been made in 2 - $3x10^{15}$ cm^{-3} n-type GaAs at 300^oK by means of optical excitation.[17] At high excitation levels ($\Delta n \approx 1.5x10^{17}$ cm^{-3}) the lifetime was $1x10^{-9}$ sec. Extrapolating to low excitation levels ($\Delta n < n_o$) gives a lifetime of about 10^{-7} sec for this material. For InAs the following measurements have been obtained:[18]

Carrier conc. (cm^{-3})	T(^oK)	τ_n(sec)	τ_p(sec)
	250	10^{-8}	
$3x10^{17}$ (P)	140	$5x10^{-7}$	$2x10^{-6}$
	77	$1.5x10^{-8}$	$4x10^{-6}$
	250	$5x10^{-10}$	$1.2x10^{-9}$
$2x10^{16}$ (N)	140	$1x10^{-8}$	$1x10^{-7}$
	77	$5x10^{-8}$	$5x10^{-6}$

The difference between electron and hole lifetimes indicates the presence of trapping effects. However, from data on the $3x10^{17}$ cm^{-3} p-type sample we can expect electron lifetimes considerably longer than 10^{-8} sec in lower carrier concentration p-type material. For this calculation we shall use 10^{-8} sec for the average electron lifetime in the graded gap region.

In order to reduce the thermally generated dark current, this device will have to be cooled to temperatures in the range 77^{o} - 200^{o}K. Electron mobilities in epitaxially grown n-type GaAs (2×10^{13} cm^{-3}) at 77^{o}K are as high as 2×10^{5} $cm^{2}/Vsec$[15] while in n-type InAs (4×10^{15} cm^{-3}) a mobility of 1.1×10^{5} $cm^{2}/Vsec$ has been observed.[16] Because of the possibility of mobility-limiting defects which may be present in the graded-gap structure due to the lattice mismatch between InAs and GaAs, we shall use the somewhat lower value of 5×10^{4} $cm^{2}/Vsec$ for electrons. Hole mobilities of the order of 10^{3} $cm^{2}/Vsec$ have been observed between 100^{o}K and 200^{o}K in both InAs and GaAs.[19] Thus, on a "best estimate" basis we shall use the following values:

$$E_1 = 0.4 \text{ eV}$$
$$E_2 = 1.3 \text{ eV}$$
$$\mu_e = 5\times10^{4} \text{ cm}^2/\text{Vsec}$$
$$\tau_e = 10^{-8} \text{ sec}$$
$$\mu_h = 1000 \text{ cm}^2/\text{Vsec}$$
$$p_o = 5\times10^{14} \text{ cm}^{-3}$$

The results are:

$$\mu_e\tau_e = 5\times10^{-4} \text{ cm}^2/\text{V}$$
$$\sigma = 8\times10^{-2} \text{ mho}$$
$$\Delta V = 0.9 \text{ V}$$
$$\ell_m' = 1.2\times10^{-2} \text{ cm} = 120\ \mu$$
$$V = 1.2 \text{ V}$$
$$P_A' = 8 \text{ W/cm}^2 = 80 \text{ mW/mm}^2$$

From these two examples it appears that a sufficient voltage can be applied to a properly designed graded gap structure to sweep most of the photogenerated electrons to the wide-gap region without excessive power dissipation. The maximum power that can be dissipated will, of course, depend on the heatsinking and on the thermal conductivity of the semiconductor. A few hundred milliwatts per mm^2 should be feasible.

Response Speed

Since the photoemission process itself is known to be fast, the response speed in the graded-gap device can be expected to be limited by the transit time (τ_t) of the electrons across the graded gap region:

$$\tau_t = \int_0^{\ell_m} \frac{dx}{v_x} = \int_0^{\ell_m} \frac{dx}{\mu_x \mathcal{E}_x} \qquad (8)$$

where v_x is the electron velocity at the position x in the graded gap region. If the length of the graded region is equal to the electron drift length, then the transit time simply equals the electron lifetime.

Example 1 ($Hg_{1-x}Cd_xTe$)

Assuming a constant field

$$\mathcal{E}_x = \frac{V-\Delta V}{\ell_m} = \frac{0.4}{1.3\times10^{-2}} = 31 \text{ V/cm}$$

For a constant electron mobility $\mu_e = 5\times10^4$ cm^2/Vsec.

$$\tau_t = \frac{\ell_m}{\mu_e \mathcal{E}_x} = 8.4\times10^{-9} \text{ sec}$$

This corresponds to a bandwidth of about 20 MHz.

To achieve a 200 MHz bandwidth ($\tau_t = 8.4 \times 10^{-10}$ sec) a field of 310 V/cm corresponding to a voltage of 5.2 V is required. The dissipated power then increases to 330 mW/mm^2.

Dark Current

As in other photoemissive devices, the detector noise in the graded gap emitter is expected to be dominated by fluctuations in the dark current. As a first approximation we assume that the dark current is determined by electrons which are thermally generated across the energy gap in the graded gap region and are swept into the wide gap region by the applied drift field. The electron current in the vacuum then will be the electron current into the wide-gap region reduced by the photoemission efficiency η_p.

The electron generation rate G_e at any point x in the graded gap region is approximately equal to the equilibrium recombination rate

$$G_e = \frac{n_o}{\tau_e} = \frac{n_i^2}{\tau_e p_o} \tag{9}$$

where n_o and p_o are the equilibrium electron and hole concentrations respectively and n_i is the intrinsic carrier concentration at point x. Due to recombination only a fraction $\exp[-(\ell-x)/L_d]$ of the electrons generated at x will reach the wide-gap region at $x = \ell$.

The dark current density then becomes

$$J_d = q\eta_p \int_o^{\ell} \frac{n_i^2}{\tau_e p_o} e^{\frac{\ell-x}{L_d}} dx \tag{10}$$

The intrinsic carrier concentration in a non-degenerate semiconductor is given by

$$n_i^2 = N_c^2 \, e^{-\frac{E}{kT}} \text{ where } N_c^2 = 2\left(\frac{2\pi kT}{h^2}\right)^3 \quad (m_e m_h)^{3/2} \tag{11}$$

If we assume that the effective masses (m_e and m_h) do not vary as a function of energy gap and that the energy gap increases linearly with x we can express E as

$$E = E_1 + \frac{\Delta E}{\ell} x \text{ , where } \Delta E = E_2 - E_1$$

and the dark current as

$$J_d = \frac{q\eta_p N_c^2}{\tau_e p_o} \int_o^{\ell} e^{-\frac{1}{kT}(E_1 + \frac{\Delta E}{\ell} x) - \frac{\ell - x}{L_d}} dx$$

Integrating

$$J_d = \frac{q\eta_p N_c^2}{\tau_e p_o} \left(\frac{\Delta E}{kT\ell} - \frac{1}{L_d}\right)^{-1} \left(e^{-\frac{E_1}{kT} - \frac{\ell}{L_d}} - e^{-\frac{E_2}{kT}}\right) \tag{12}$$

Since E_1 must be much larger than kT in order to avoid excessive thermal excitation, then for $\ell = \ell_m \approx L_d$

$$\frac{\ell}{L_d} \ll \frac{E_1}{kT} \text{ and } e^{-\frac{E_2}{kT}} \ll e^{-\frac{E_1}{kT} - \frac{\ell}{L_d}} \text{ ,}$$

and J_d can be expressed in terms of the intrinsic carrier concentration n_{i1} at the energy gap value E_1 as

$$J_d = \frac{q\eta_p\eta_t kT\ell_m n_{i1}^2}{\tau_e\, p_o\, \Delta E} \quad , \tag{13}$$

provided also that $\Delta E \gg kT$. Here η_t is the transmission efficiency of the graded region $\eta_t = \exp(-\ell/L_d)$.

Example 1

For the $Hg_{1-x}Cd_xTe$ at 77^oK, $n_{i1} = 1.3 \times 10^{13}$ cm^{-3} (for $E_1 = 0.1$ eV). For the earlier used values of $\tau_e = 10^{-8}$ sec, $p_o = 10^{15}$ cm^{-3}, $\Delta E = 1.2$ eV and $\ell_m = 1.3 \times 10^{-2}$ cm and for an overall efficiency $\eta_p\eta_t = 0.1$, Eq. (13) gives a value of 2×10^{-5} A/cm^2. This relatively large dark current value indicates that for a 10.6 μ detector a lower operating temperature may be necessary. At 50^oK the intrinsic carrier concentration is 1.5×10^{11} cm^{-3} corresponding to a dark current of 1.7×10^{-9} A/cm^2, a value which may be tolerable for some applications. The noise equivalent power in a 1 Hz bandwidth is given by

$$P_N = \frac{E_\lambda}{\eta} (2eJ_dA)^{1/2} \tag{14}$$

where E_λ is the photon energy and A is the area of the detector, and η is the overall quantum efficiency $\eta = \eta_p\eta_t$. For $E_\lambda = 0.1$ eV and $A = 0.25$ cm^2, $\eta = 0.1$, and an operating temperature of 50^oK, $P_N = 1.1 \times 10^{-14}$ $W/Hz^{1/2}$.

Example 2

For $Ga_{1-x}In_xAs$ at 150^oK n_{i1} is estimated at 1.2×10^{11} cm^{-3} (for $E_1 = 0.4$ eV). Using the values $\eta_p\eta_t = 0.1$, $\ell_m = 1.2 \times 10^{-2}$ cm, $\tau_e = 10^{-8}$ sec, $p_o = 5 \times 10^{14}$ cm^{-3}, and $\Delta E = 0.9$ eV, the dark current

$J_d = 8\times10^{-9}$ A/cm^2. For an area of 0.25 cm^2 $P_N = 10^{-13}$ W/Hz$^{\frac{1}{2}}$. The operating temperature would have to be lowered to about 130°K to achieve a P_N value of 10^{-14} W/Hz$^{\frac{1}{2}}$.

Substituting Eq. (13) into Eq. (14) gives

$$P_N = qE_\lambda n_{il} \left(\frac{2kT\ell_m A}{\eta\tau_e P_o \Delta E}\right)^{\frac{1}{2}} \qquad (15)$$

For the detectivity $D^* = \frac{A^{\frac{1}{2}}}{P_N}$ we obtain

$$D^* = \frac{1}{qE_\lambda n_{il}} \left(\frac{\eta\tau_e P_o \Delta E}{2kT\ell_m}\right)^{\frac{1}{2}} \qquad (16)$$

Design Considerations

Since one of the important requirements is adequate cooling of the graded-gap cathode, we propose mounting the narrow gap side on a metal heatsink by first metallizing the semiconductor surface by such means as plating or evaporation in order to improve contact. This heatsink then would also provide one of the electrodes for applying the bias. The incident radiation in this case would enter through the cesiated surface and be absorbed at a point in the graded region at which the energy gap equals the photon energy. Thus, for shorter wavelengths the absorption would occur closer to the cesiated surface. The other electrode for applying the bias would be an ohmic contact to the thin p^+ region at the wide-gap surface. (The area under the contact would probably not be used for photoemission.)

The required depth of the p^+ layer can be estimated for a given doping if the amount of band-bending is known. The depth d is given by

$$d = \left(\frac{2\epsilon\phi_s}{qp^+}\right)^{1/2}$$

where ϕ_s is the surface potential and p^+ is the carrier concentration in the heavily doped layer. For $\phi_s = 0.5V$, $\epsilon = 16\epsilon_o$ and $p^+ = 10^{19}$ cm^{-3}, d = 100 Å. The best way to achieve layers of controlled depth and doping may be by means of ion implantation. Since CdTe has been doped p-type to concentrations of 10^{17}-10^{18} cm^{-3} and a depth of about 3000 Å by implanting As,[20] such implants could be tried for making the p^+ layers in the graded $Hg_{1-x}Cd_xTe$ device.

Because of absorption of impurities by the surface, cleaning of the surface just prior to cesiation is found to be a crucial step in fabrication of the GaAs and other III-V compound photoemitters.[2] GaAs has been cleaned simply by heating to about 600°C in the vacuum. This technique should work for the $Ga_{1-x}In_xAs$ graded gap device. Because of the high vapor pressure of Hg, heating may cause damage in the case of $Hg_{1-x}Cd_xTe$. Other cleaning techniques such as sputter-etching may be tried.

With regard to the graded gap region, it should be pointed out that the exact linear grade and constant p-type conductance assumed in the calculation will not be necessary in a practical device; in fact, in certain cases these may not be the optimum conditions for electron transport across the region. If the mobilities and lifetimes varied in a known manner as a function of energy gap in the graded gap region, then the criteria of Appendix I could be used to optimize the energy gap and the doping profile.

APPENDIX I

Current Flow in a Graded-Gap Region

The one-dimensional electron current density J_e in the x direction can be expressed as

$$J_e = n\mu_e \frac{d\phi_e}{dx} \tag{17}$$

where n is the electron concentration and ϕ_e is the "electro-chemical" potential given by

$$\phi_e = -qV + E_c + E_F \tag{18}$$

where V is the electrostatic potential, E_c is the conduction band extremum and E_F is the electron Fermi level. The electron concentration and the Fermi level in the nondegenerate case are related by

$$n = Cm_e^{3/2} e^{\frac{E_F}{kT}} \tag{19}$$

where C is a constant. Combining Eqs. (17), (18), and (19) yields

$$J_e = qn\mu_e \left[\frac{d(V_c - V)}{dx} - \frac{3kT}{2qm_e^*} \frac{dm_e^*}{dx} + \frac{kT}{qn} \frac{dn}{dx} \right] \tag{20}$$

where $V_c = E_c/q$. For holes

$$J_h = qp\mu_h \left[\frac{d(V_v - V)}{dx} + \frac{3kT}{2qm_h^*} \frac{dm_h^*}{dx} - \frac{kT}{qp} \frac{dp}{dx} \right] \tag{21}$$

where V_v is the potential of the valence band extremum.

In order to make simplifying approximations we estimate the relative size of the three terms in Eqs. (20) and (21) for the $Hg_{1-x}Cd_xTe$ device. For electrons the electric field $d(V_c-V)/dx$ has a value of 30 V/cm. By comparison the equivalent field due to the effective mass gradient is about 0.5 V/cm at $50^{\circ}K$ (using effective mass values of 0.029 and 0.096 for the 0.1 and 1.3 eV energy gap regions respectively[13]). For an electron concentration which varies with x as $\exp(x/L_d)$ the term involving a carrier gradient reduces to kT/qL_d, which has a value of 0.3 V/cm. For holes the electric field $d(V_v-V)/dx$ is 120 V/cm compared to 0.35 V/cm and 1.4 V/cm for the fields due to the effective mass gradient and the carrier gradient respectively, if it is assumed that the hole effective mass varies from 0.3 to 0.6 and the hole concentration from 5×10^{15} to 5×10^{14} cm^{-3} in going from the narrow gap region to the wide gap region. Thus, for the cases examined the diffusion terms which involve carrier and effective mass gradients can be neglected. If in addition $n\mu_e \ll p\mu_h$ then the electrostatic field is determined only by the hole current.

The determination of the transmission efficiency of photo-electrons across the graded gap region involves solving the continuity equation

$$\frac{1}{q} \operatorname{div} J_e = - \frac{n-n_o}{\tau_e} \qquad (22)$$

subject to boundary conditions at both ends of the graded region. Since the boundary conditions are not well known, however, we estimate the transmission efficiency on the basis of bulk parameters:

For a constant electron drift field $\mathcal{E} = \frac{d(V_c - V)}{dx}$, $J_e = qn\mu_e \mathcal{E}$ and Eq. (22) can be written as

$$\mu_e \mathcal{E} \frac{d\Delta n}{dx} = - \frac{\Delta n}{\tau_e} \qquad (23)$$

which has a solution $\Delta n = \Delta n_o \exp(-x/L_d)$ with $L_d = \mu_e \tau_e \mathcal{E}$. Thus, a photoelectron current $J_{eo} = q\mu_e \mathcal{E} \Delta n_o$ injected at point $x = 0$ will be attenuated by $\exp(-x/L_d)$ at point x, and the drift length L_d can be used to estimate an acceptable length for the graded gap region.

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13. ABSTRACT

A new scheme is proposed for achieving photoemission from semiconductors at infrared wavelengths from about 1μ to well beyond 10μ. The device consists of a graded-energy-gap p-type semiconductor with a low work function coating on the wide-gap side. Electrons, which are photoexcited from the valence to the conduction band by long wavelength radiation in the narrow-gap region are drifted by an applied electric field into the wide-gap region from where they are emitted into vacuum. Graded-gap $Hg_{1-x}Cd_xTe$ is considered for a photoemitter covering wavelengths to about 12μ and both $Ga_{1-x}In_xAs$ and $InAs_xP_{1-x}$ are proposed as possible alloys for 3-μ photoemission. Preliminary calculations made with available parameter values indicate that the scheme holds considerable promise. For the simplest case of a linearly graded gap and a constant conductance, expressions are derived for the length of the graded region required to minimize power dissipation and for the speed of response. A calculation is also made of the dark current which results from thermal generation in the narrow-gap region in order to determine the operating temperature required for achieving a desired noise-equivalent power (P_N) at any wavelength. For an overall quantum efficiency of 10 percent, an estimated operating temperature of 50°K is required for achieving a P_N of about 10^{-14} W/Hz$^{1/2}$ in a 12-μ detector; for a 3-μ detector this P_N value can be achieved at approximately 130°K.

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