Photoneural device structures

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Abstract

Photoneural systems are a class of hybrid, optoelectronic processors designed to mimic rather closely the neural mechanisms and architectures involved in visual perception and other cognitive processes. In these systems optical linkages provide complex and adaptable neural-like interconnections between different synaptic centers which may be realized as autonomous elements of monolithically integrated optoelectronic arrays. The perception of sensory stimuli is mediated by a vastly complex hierarchy of "permeatively" linked processes. However, each step in perception seems to involve relatively simple "antagonistic" responses and the structure of perceptual responses remain topographic coherent when "mapped" to various subsystems of the brain. The topographic invariance of cognitive data transmission is suggestive of optical imaging operations and is the essential rationale for photoneural design. The basic synaptic elements are autonomous, optoelectronic processors which are, essentially, optical transceivers activated by contrasting input stimuli. Recent developments in technology make feasible a class of promising photoneural devices which are simple integrated configurations of light emitting diodes, heterojunction phototransistors and liquid crystal light switches.

Introduction

The appellation "photoneural" is used to span a set of design concepts based on the premise that optic and optoelectronic operations can be configured to mimic the elemental mechanisms operating in the central nervous system (CNS). Photoneural processors are envisaged as realizations of cognitive functions within which optical propagation provides adaptable neural-like interconnections to link a manifold of "synaptic" centers which are implemented as autonomous elements of monolithically integrated optoelectronic arrays [1,2]. At the moment, photoneural design is a speculative concept, but recent advances in optoelectronic technology make practicable photoneural device structures eminently feasible. Study of photoneural systems could have an important impact on cognitive research and simple photoneural processors might be usefully employed as "front-end" processors to reduce the computational burden in artificial perception systems. This paper describes, in particular, a promising class of optoelectronic device structures which respond much like neuronal substructures.

The neurological context

At a biological level, much is known about the vastly intricate cellular mechanisms and patterns of interconnection in the CNS [3,4]. The profound scientific challenge is to understand how these constituent processes globally aggregate to effectuate mentation - i.e. perception, learning, memory, consciousness and self-awareness. The emerging picture of the neural organization of the CNS is not readily characterized in the conventional language of computer architecture. Information streams converge and diverge in exquisitely complex patterns so that the designations serial, parallel and distributed all seem to apply to some limited extent, but are not particularly helpful as design metaphors. We suggest the designation permeative to characterize architectures in which the execution of several distinct processes simultaneously permeates a conjoint set of neural processors.

Study of visual and somatic sensory perception yields the most revealing insights into the cellular mechanisms and organizations mediating cognitive function. The accessibility of peripheral sensory receptors and correlative cortical areas facilitates the resolution of sensory cytoarchitectures and direct experimental measurements of cellular transformations of stimulus/response patterns within these cytoarchitectures. It may be infered that the neural "principles" deduced in these observations also operate in less accessible structures of the brain and cognitive functions. Since photoneural notions have been inspired by study of early phases of vertebrate vision, it is necessary to recapitulate, briefly, some of the key metaphorical principles operating in the retina and visual cortex to establish a context for discussing photoneural design.

As schematically indicated in Fig. 1(a), the initial light intensity distribution incident on the eye is transformed by the retinal receptors (R) into a spatially encoded pattern of neural signals [5]. The initial encoding of the visual stimulus is sequentially transformed as the information flows through a hierarchy of cellular layers from receptors to the axons of the ganglion cells (G) which aggregate to form the optic nerve and carry the retinal output to the brain. Although the code transformation at each intercellular synapse is simple, mechanisms of lateral inhibition among neighboring cells lead to output responses which accentuate contrast. Indeed, an overwhelming body of evidence in both psychophysics and neurophysiology supports the premise that sensory perception (and, perhaps, all cognition) builds on fundamental neural processes which are responsive to stimulus change and relatively insensitive to stimulus level [3,4,6]. The first perceptual steps, in particular, are described as responses to "spatial antagonism." At the lowest level, lateral inhibition is the cellular locus of the perceptually described center/surround antagonism in which a given ganglion cell is sensitive to the contrast in excitation between a particular central field and its enveloping surround region. At higher levels, lateral inhibition leads to discriminatory responses of increasing spatial and temporal complexity.

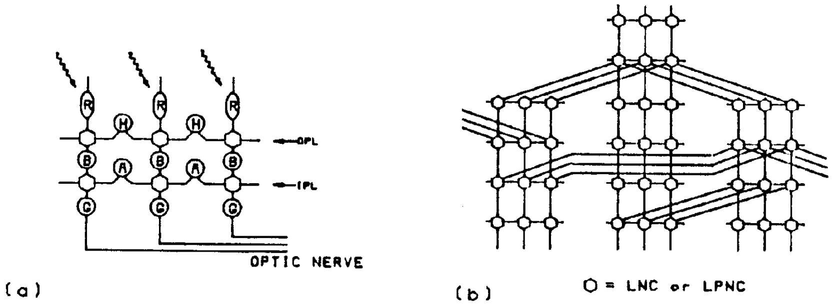

FIGURE 1. Schematic neural architectures: (a) retinal cytoarchitecture; (b) part of a "permeative" system.

Of course, the ultimate, basic datum of neural information is the value of the electrical potential across a cell membrane at a particular location in the neural network. In the retina, as in all parts of the CNS, there are two distinct formats for representing and communicating neural information - viz. "slow" and "action" potentials [3,4]. In the receptors, the light stimulus is photoelectrical transformed into a neural excitation. An increase in incident light intensity within the receptor field invokes an analog or graded "hyperpolarization" (decrease) in the level of the local membrane potential which spreads conductively along the membrane to all parts of the cell [5]. By convention, this diffusive, analog mode of data transmission is characterized as the "electrotonic spread of slow potentials." At the other end of the retina chain, as is more common throughout the CNS, information in the ganglion cells is represented and transmitted as "nerve spikes" or short pulses of fixed magnitude. Although the pulses occur in bursts, the spiking rate is a direct measure of the excitation level. As the spikes or "action potentials" propagate along the nerve, mechanisms of electrochemical regeneration act to maintain constant pulse shape and amplitude. The action potential mode of data transmission is a kind of pulse interval coding and has obvious advantages for robust communication over long distances.

At the simplest perceptual level, the receptors show a maximum response for spot illumination centered on the cell and relatively little response for an annular illumination surrounding the cell - i.e. the incident light distribution is spatial encoded or sampled. In contrast, the interconnecting horizontal cells (H) have very broad receptive fields with spot and annulus producing equivalent hyperpolarizing reponses. The responses of two classes of bipolar cells (B) exhibit the first hints of significant stimulus differentiation. In one class, the cell is hyperpolarized by the spot stimulus to signal an "on" response and in the other the cell is depolarize to signal an "off" response. The crucial point is that in both cases a simultaneous annular illumination antagonizes the potential change and reduces the effect of the center illumination. In hierarchical terms, the outer plexiform layer (OPL) seems to mark the first significant step in the process organization. Receptor, bipolar and horizontal cells are connected by a complex network of pre- and postsynaptic processes within a relative thin physical layer and this synapse generates a clearly identifiable center/surround response in the bipolar cells [5]. At this first layer of the visual hierarchy, the temporal character of the stimulus does not appear to be of any significance. In striking contrast, the amacrine cells respond only to temporal changes in illumination and are the first processes to exhibit temporal antagonism and adaptivity. The inner plexiform layer (IPL) marks the second significant step in the visual hierarchy. Again, the bipolar, amacrine (A) and ganglion cells are connected by pre- and postsynaptic processes within a relative thin physical layer. In most vertebrates, there are two distinct types of ganglionic response. The cells of one population (X-cells) synapse mainly with bipolar cells and mirror the spatial and temporal response of those cells. The synaptic process is, essentially, an "analog-to-digital" converter that encodes the slow potential presynapic excitation as action potential postsynaptic excitation for transmission to the brain. The ganglion cells of other populations (Y-cells) synapse to some degree with amacrine cells and, hence, mirror the transient temporal behavior of those cells.

Many of the axons of retinal ganglion cells project to the various layers of the thalmic lateral geniculate nuclei (LGN). Cellular recordings of potentials in the LGN show responses akin to the ganglion reponses. In particular, the concentric center/surround antagonism is the dominant response, but with a heightened contrast. The LGN functions essentially as a neural relay center and the principal cells of the LGN radiate to various layers of the visual cortex. As was first shown in the famous work of Hubel and Wiesel, cortical cells continue to exhibit responses of spatial antagonism [3,4,6]! However, the patterns of sensitivity are quite diverse and not unambiguously resolved. The least ambiguous responses are found in the, so called, "simple" cells which are most sensitive to bar or line patterns of specific angular orientations and at particular retinal locations. The "complex" cells of the visual cortex are also sensitive to lineal properties, but the position of stimulus in the retinal field is less critical.

Detailed neurobiological considerations of this sort may be generalized to provide a context for framing architectural principles. An important, elegant and yet elusive concept in neural architecture is that of a <u>local neural circuit</u> or LNC [7]. The term is defined and used so broadly it would <u>appear, at outset,</u> to convey little of substance. The physical boundaries of a LNC are functionally defined and might encompass a portion of a single nerve cell, an aggregate of many cells or a module of many identical local circuits. The OPL and IPL synapses are prototypical of the simplest type of LNC. However, the scale of LNC aggregation ranges from such simple inter-cellular synaptic junctions to columnar organized components of large entities of the brain (viz. neocortex, thalamus, limbic lobe, etc.). A LNC functions as an independent integrative unit which through-processes information available at a specific set of convergent inputs terminals, but the character of the response available at a set of divergent output terminals depends on the <u>state or condition</u> of the component elements. The internal "wiring" of a LNC reflects the <u>influences</u> of both genetic and epigenetic cell development [4]. When a particular neural element (e.g. synapse, neuron or local circuit) is incorporated in more than one LNC, activity in one circuit <u>conditions</u> the response of others and it, thereby, provides a mechanism for cross-linking <u>signals</u> in independent neural pathways. This intricate cross-linkage among distinct processes suggests a <u>permeative</u> model of process organization wherein distinct and numerous processing sequences <u>share and</u> interact within a conjoint set of cellular elements (i.e. the processes permeate the cells).

The metaphor of permeative neural organization is an alternate way of expressing the prevalent view that cognitive processes are mediated by multiple and dynamic interactions of neural subsystems distributed over many parts of the brain [3]. Figure 1(b) schematically depicts a portion of such a multiply interconnected network wherein LNC's are symbolized as hexagonal cells. Although intended as an "all purpose" neural diagram, the center subsystem is drawn to suggest a retina interconnected to higher order brain centers (e.g. to the lateral geniculate nucleus and on to the visual cortex). The figure emphasizes the kind of organizational dichotomy between "centrally" (vertical) and "laterally" (horizontal and diagonal) directed neural pathways found in retinal organization. It is a striking and powerful observation that this dichotomy seems to be valid and useful in the study of cellular organization in other subsystems and for analysis of processes at different levels of abstract. The interpretation at a high level of abstraction takes the local circuits as large entities of the CNS, the centrally directed pathways as the flow of information in the various sensory modalities through a hierarchy of perceptual stages of ever increasing complexity and the laterally directed pathways as inter-modality or inter-entity interactions. An interpretation at a lower level takes, for example, the local circuits as neural synapses, the centrally directed chains as signal pathways of the receptive field of a particular sensory receptor and the laterally directed chains are cross-comparative operations.

One aspect of the dichotomy is that centrally directed processes maintain some kind of <u>topological invariance</u>, as suggested in Fig 1(b). The first steps in visual perception (i.e. responses of ganglion cells) preserve strict topographic relationships. A stimulus attribute (e.g. center/surround-on) activates a ganglion cell in close proximity to the initial stimulus. Given the structure of the eye, this organization does not seem surprising. What is surprising, is that organization continues in the lateral geniculate nucleus and on into the areas of the visual cortex [3,4,6]. The attributes of the stimulus are refined, but they continue to be organized topographically.

Neurophysiologist, over the last decade, have been able to identified many different examples of "columnar" structures of cortical cells which function as modular, elemental sensory processors [7,8]. Of particular significance, are the much studied columnar structures in "area 17" of the visual cortex. These structures are the examples par excellence of permeative neural organizaton. In brief, a column is a cortical representation of a particular stimulus attribute (e.g. ocular dominance, line orientation or color) which preserves topological or retinotopic relationships. These columns are LNC's and, as such, function as input-output processor. However, columns representing different attributes infuse or permeate the same cortical space and, hence, local lateral processes lead to higher level responses which preserve topological relationships. The processing of a particular attribute may also occur in parallel at other cortical locations or in other entities. Again, at each location, it appears that the processes are organized into patterns which reflect the topographical relationships within the initial sensory stimulus [9]. In the sensory realm at least, "mapping" or topographical imaging is an important characteristic of neural communication. It is this observation which leads us to believe that optics offers us unique opportunities in dealing with tasks in artificial sensory perception.

Local photoneural circuits

The photoneural strategy is based on the proposition that the permeative metaphor of neural process organization can be effective interpreted in an adaptive optical system. Accordingly, Fig. 1(b) is re-interpreted as a schematic representation of a portion of a multiply interconnected, distributed photoneural system of local information processors interacting via lightwaves propagating through a progression of encoded optical channels. The processors are hybrid optoelectronic interpretations of the previously discussed local neural circuits and are, henceforth, refered to as local photoneural circuits or LPNC's.

In the most direct interpretation, the channels are spatial-encoded operations by which the output of one LPNC is imaged at or broadcast to the input of another. The basic "data type" in a photoneural system is a spatial-encoded light intensity distribution which is taken to represent a sensory or cognitive response at a given hierarchical level within a specific processing module. A basic data transfer involves the mapping of a complete representation of the response at one level to other levels of the same module or to other processing modules by means of optical imaging techniques. The word mapping is used to emphasize the notion that imaging operations maintain topological relationships within the data type. It is essential to note that a single mapping operation may be multiplexed to carry many topological representations in parallel since the light intensity distribution may be independently wavelength (color), polarization and/or time encoded. Thus, light-mapped, cognitive data structures may carry several stimulus attributes in parallel. This aspect of photoneural organization is of critical importance, since, as noted above, such multi-dimensional mappings seems to be precisely the kind of permeative process organization found in the columnar structures of the cerebral cortex.

Clearly, the local processing unit - the LPNC - is the crucial element in the photoneural concept. It is the optoelectronic analog of a single neural synapse. Specifically, an individual LPNC unit performs three functionally distinct operations. The initial or input operation includes both the decoding and the photoelectric transduction of the incident optical signals. The intermediate or processing operation is a simple electronic circuit which mimics the integrative transformation of an analogous local neural circuit. Following the synaptic analogy, the output of the electronic circuit is, in most cases, a discriminatory or antagonistic response, but is adaptable or programmable to allow for "epigenetic" development of the overall system response [4]. The final or output operation involves the re-encoding of the electronic response as lightwaves for transmission to other LPNC's.

Given this somewhat abstract, general specification of LPNC function, one might imagine, at outset, many equally attractive realizations. However, the large scale and complex connectivity of any potential interesting photoneural systems imposes critical constraints on LPNC design. Above all, LPNC's must be simple to produce in very large numbers and accessible by standard optical imaging techniques. Both conditions militate realizations that are compatible with a planar integration and microfabrication. Indeed, the photoneural concept has been inspired and is made practicable by the recent advances in heterojunction technology. Of particular importance, has been the development of sophisticated, thin-film epitaxial crystal growth techniques. Given the technology base, the options in integrated opto-electronic device design have become exceedingly flexible. Following Kroemer [10,11], we may take as a "technological premise" the availability of almost any kind of multi-layered structure of multi-component III-V compound semiconductors of high crystal perfection with precise control over composition, composition profile, doping levels and layer thickness if there is sufficient reason to build it!

There is a further general comment on LPNC design. In various, potentially feasible LPNC realizations, the particulars of input and processing operations may differ in significant ways, but it is the output operation which poses the most difficult technical problems and which has greatest impact on overall system design. In one class of realizations, hereafter designated as *light generating* local photoneural circuits or LG-LPNC's, the output electrical response controls the drive current of a light emitting diode (LED) to *generate* a light response directly. In a second class, hereafter designated as *light switching* local photoneural circuits or LS-LPNC's, the output electrical response controls the voltage across an electro-optic switch element and, hence, the response is *read* by an externally generated light probe. The advantages of LG-LPNC realization are twofold: design and fabrication requires but a minor extension of current integrated circuit capabilities and the individual units are highly autonomous in the sense of requiring only power supply connections. LG-LPNC structures are technically elegant since all three operations are implemented within a single microcircuit of a simple heterostructure configuration. Of course, the disadvantages of LG-LPNC realization arise from the inherent inefficiency of injection electroluminescence. The heat generated by a individual unit is proportional to, but orders of magnitude greater than signal levels. Thus, systems incorporating LG-LPNC's must be designed to run at low average light levels, to minimize thermal degradation and to maximize electroluminescent efficiency.

Since electro-optic effects are voltage dependent, light switching requires minimal control power and, hence, obviates most of the thermal dissipation problems associated with light generation. The major problem, of course, is that the technology for an effective integrated semiconductor electro-optic switch is not presently available. In the long term, the development of "quantum-well" or "excitonic" switches may make a truly integrated LS-LPNC feasible [12]. In the near term, however, an eclectic mix of semiconductor and liquid crystal technologies affords a reasonable compromise [13,14]. Discussion of LS-LPNC realization is complicated by the fact that the overall system design must accommodate read light beams. However, it is possible to integrate semiconductor laser read beams into LS-LPNC arrays to greatly facilitate spectral multiplexing operations. In light of the rapid developments in LCD technology, the electro-optic option appears promising and is the principal focus of the discussion that follows.

Although there are several possibilities, the examination of a specific LPNC realization best illustrates key photoneural design issues. One of the most promising designs is a device structure inspired by reports of an new and innovative class of image processing devices [15,16]. These devices are monolithically integrated planar arrays of optoelectronic image elements within which incident light signals are amplified and, if need be, converted in wavelength. Each image element of the array is an electrically isolated, multi-layered semiconductor heterostructure. The top and bottom layers of the heterostructure are optically transparent, electrical conductors connected to effectuate a voltage bias across the element. A sequence of three layers within the structure form, in sequence, the emitter, base and collector of a bipolar heterojunction phototransistor (hereafter denote HPT). Light incident on top surface of the element passes through the emitter into the base region of the HPT where it is absorbed and generates excess electron-hole pairs. The excess photogenerated minority carriers are drawn off by a reverse bias across the base-collector junction and the resultant charge separation induces a small "photovoltaic" shift in the base potential. Since the base is floating, this shift effects an exponential increase in the forward current across the base-emitter. If emitter injection efficiency is high and the base region thin, most of this light induced forward current is collected at the base-collector junction to yield a high net photoelectric gain. The photocurrent generated and amplified within the HPT sequence flows directly into an adjacent second sequence of layers which form a double heterojunction light emitting structure designed to maximize the overall injection electroluminescent efficiency and to achieve specific output spectral characteristics. Finally, the amplified and spectrally shifted optical signal is re-radiated out through the bottom surface of the element.

These devices demonstrate at least two significant attributes of heterostructure physics. A fundamentally important transport property is the marked asymmetry in majority carrier injection across a pn heterojunction. The asymmetry varies exponentially with the difference in bandgap energies of two semiconductors in the sense that the forward current is dominated by the component injected from the wide-gap region into the narrow-gap region. In the heterojunction version of a phototransistor with narrow-gap base region the asymmetry leads to a high emitter injection efficiency which is relatively insensitive to other design parameters. Taken together with the dimensional and compositional control afforded by epitaxial methods, this enhanced emitter efficiency has generated a resurgent interest in bipolar technology [10,11], in general, and phototransistors [17], in particular.

As these devices demonstrate, the shift in the intrinsic optical absorption edge at a heterojunction provides the means for spectral control of optical penetration and, thus in principle, the means for injecting signal information at any depth within a heterostructure. In this sense, HPT's afford a unique opportunity for *three-dimensional* process integration. Specifically, the spectral response or sensitivity of a HPT sequence is relatively constant over an activation-band bounded by two bandgap energies. Incident light with photon energy greater than the bandgap of the emitter layer is absorbed within an absorption length from the surface of the device and, thus, a device with a moderately thick emitter region has a minimal photo response. Light with photon energy less than the emitter bandgap, but greater than the base bandgap, has maximal response since the light penetrates through the emitter region and photogeneration occurs close to the base-collector junction in the thin base region. Light with photon energy less that the base bandgap passes through the complete sequence without appreciable interaction.

These high optical gain amplifiers demonstrate the feasibility of the input/output operations of a of LG-LPNC. In addition, they exhibit a mode of vertical organization akin to that found in the retina and in cortical tissue. The major design issue is find means to effectuate the processing operation within such vertically organized structures. As previously noted, the essential processing operation is an integrative response activated by antagonistic or contrasting stimuli - e.g. the center/surround response. In particular, we need optoelectronic means for realizing lateral inhibition. Many schemes for doing optoelectronic logic have been discussed. For example, basic photodetector-photoemitter combinations have been used to realize logical AND and OR operations [18,19]. However, inhibition requires, in effect, the EXOR or "NOT-AND" operation. Said another way, inhibition requires the inverse operation to effectively produce a subtraction. In the realm of incoherent optics, unfortunately, real time subtraction of images is a difficult problem since the magnitude of the light intensity is a unipolar variable.

We have developed [1], however, several, simple optoelectronic modes for realizing lateral inhibition which are all based on the paradigm of inversion by light activated current stealing. Figure 2(a) illustrates the operation of one of the most promising versions of the paradigm in which input photodetectors and an output photoemitter are arrayed in a single node "star" configuration. One limb of the star is the conduction path from node-to-ground through a light emitting diode. The other limbs are paths through a set of HPT's to various supply voltages. Some of the HPT's are biased to provide, when light activated, a source of drive current for the LED while others are biased to sink or "steal" the excitation current when light activated. The light incident on the first group may be characterized as an "excitatory" stimulus and that on the second as an "inhibitory" stimulus. When the net stimulus invokes equal currents in the two HPT's, the voltage at the central node is close to ground ("resting potential") and no current flows in the LED! As the excitatory light increases above this quiescent level, the voltage at the node rises to the threshold "cut-in voltage" of the diode. Above threshold, the light output of the LED is a direct measure of the net excitatory stimulus. The biasing voltages may be separately controlled to compensate for asymmetries, to modify thresholds or change overall functional characteristics. Figure 2(b) shows an obvious light switching variant of the basic star configuration. For net excitatory activation, current flows to the electrode of a LCD pixel and the stored charge determines the state of the optical switch. Below a pre-set bias, any net inhibitory current leaks through the diode leaving the pixel uncharged. Since most modes of liquid crystal switching are functions of the magnitude of field across the electrode, the diode provides an essential non-linearity in the LS-LPNC response. The circuit has "short term memory" in the sense that the charge on the electrode is the integral of the net excitatory current over a time period determined by the leakage RC constant of the LCD element.

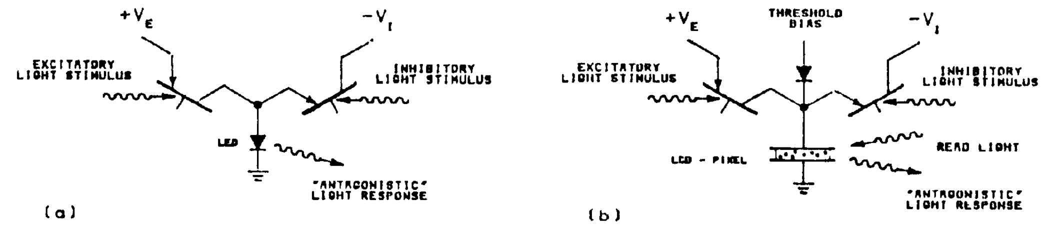

FIGURE 2. Basic LPNC "star" configuration: (a) LG-LPNC version; (b) LS-LPNC version.

The antagonistic response of the star configuration closely mimics the operation of a neural synapse [3,4]. In fact, the physical mechanism active in this device are quite analogous to mechanisms operating in neuronal membranes. The transistors as "back-to-back" diodes electrically isolate the central node in much the same way that the mechanism of selective ionic permeability in the cellular membrane electrically isolates the interior of a neuron. The stimulus dependent conductive response of the phototransistors operates akin to the chemical-gating of ion channels by neural transmitters. The non-linear response of the LED (or the shunting diode in the LS-LPNC configuration) to changes in nodal potential is similar to the characteristic, "excitable" response [3,4] of the voltage-gated ionic channels to changes in membrane potential.

The simple star configuration is a rather elegant and practicable neural analog. Figure 3 shows a discrete circuit representation of a modification of the basic LS-LPNC configuration that incorporates two important functional enhancements. One extremely important enhancement is the addition of multispectral control of the LPNC response. As noted above, the response of an HPT sequence is spectrally bounded by the bandgaps of the emitter and base regions. However, by judicious selection of semiconductors two or more separately addressable HPT sequences may be stacked one above the other. A light signal will penetrate a HPT sequence if its photon energy is less that any bandgap in the sequence. In Fig. 3 two spectrally distinct HPT sequences are schematized as series elements and the response of the particular star limb is, essentially, the product or "correlation" of the excitations at two distinct wavelengths. It is assumed that the signals labeled "excitatory/inhibitory" are at a wavelengths within the activation-band of the upper HPT and are completely absorbed there. The signal labeled "control" is assumed to be at a wavelength within the activation-band of the lower HPT, but long enough to allow for penetration of the upper layers. Thus, the longer wavelength control signal acts as a switch or gate to activate the circuit's response at the other frequency. This easily achieved, multispectral response characteristic adds greatly to the potential utility of heterojunction LPNC realizations. In this regard, the LS-LPNC realization is particularly important since sharply defined response signals may be derived from dedicated injection laser read signals. Thus, response of a particular sub-systems within a photoneural system may be color encoded for broadcast to other units in the system. The control may be used to activate a single device, to dynamically program the operation of a whole array, to carry in parallel distinct stimulus attributes, to produce contrast reversal or to effectuate adaptive feedback responses.

The operation of the simple star configuration much resembles the "slow potential" operation of the retinal receptor, horizontal, and bipolar cells as discussed above. However, a second enhancement, in the form of a shunting "Shockley four layer diode" (SFLD) [20] across the LCD pixel, transforms the operation to an astable mode which resembles the more common neural "spiked potential" operation of the amacrine and ganglion cells. Initially a net excitation of the cell, results in a charging current to the LCD element with negligible leakage through the SFLD in its high impedance state. When, the voltage across the element exceeds the SFLD threshold, the SFLD switches to its low impedance state and rapidly discharges the capacitor. After discharge the SFLD returns to the high impedance state and capacitor is recharged. Thus, the switched output light pulse rate directly measures LPNC excitation. Unfortunately, the maximum switching rate is limited by the relatively long liquid crystal decay times.

Figure 4 suggests an integrated realization of the LG-LPNC depicted as a discrete circuit in Fig. 3. The fabrication of such an array might start with a substrate composed

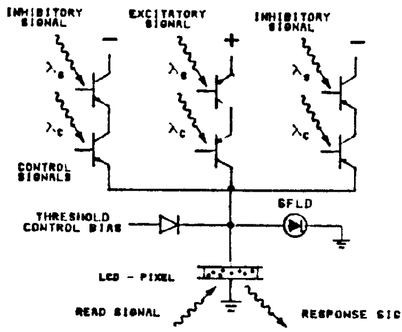

FIGURE 3: Multispectral LS-LPNC with pulse rate encoded response.

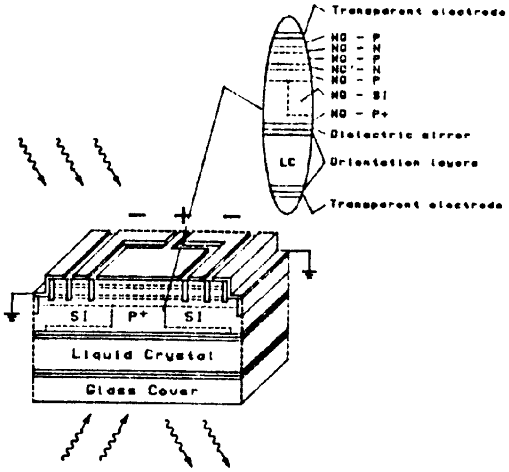

FIGURE 4: Heterojunction LS-LPNC

of an matrix of electrically isolated, highly conducting (P+) islands formed by conventional diffusion of acceptor impurities in a semi-insulating (SI) wafer of, say, intrinsic GaAs. All other elements could then be deposited in a single epitaxial growth run. The insert indicates the essential layer sequences where the notation "WG" (wide gap) designates a III-V alloy with a larger bandgap energy and "NG" (narrow gap) designates the of NG' less that of NG. Light excitation would be incident at the top, pass through transparent electrodes and be absorbed in an appropriate layer. The element schematized in Fig. 4 is half of a center/surround pixel. The central excitatory HPT might be isolated from the surrounding inhibitory HPT by an ion beam damaged insulated barrier (shown shaded in sketch). The outer, damage isolated heterostructure is the shunting SFLD. (Unfortunately, it would be necessary to compensate the upper WG-P layer to WG-N in the SFLD sub-structure after the epitaxial growth stage). At the outer edges of the pixel a step might be etched to the nodal WG-P layer to afford contact for the leakage diode, shown as a Schottky barrier diode [20]. The lower side of semiconductor substrate would provide the support for a reflective LCD. The initially diffused conducting islands define the pixel electrodes. A dielectric mirror and a layer of surface coupling agent would be deposited over the semiconductor surface, as indicated. For maximum flexibility and to avoid the troublesome complications of integrated polarizers, the configuration in Fig. 4 assumes the "guest host" mode of dichroic light switching [13,14] and an external, polarized laser read beam. The mixture of pleochronic dye and liquid crystal molecules is sealed to the substrate by a glass cover which also supports the common electrode and a second polymer coating alignment layer.

Conclusions

There is no doubt that LPNC arrays could be realized with current technology. It is equally evident that such arrays could find direct application as simple "front-end" processors in machine vision systems. Device structures similar to those discussed above could be easily statically configured or dynamically programmed to function as two-dimensional feature detectors (e.g. edge, line, line termination, blob, etc.), spatial filters or motional detectors. In this relatively modest context, one particularly attractive possibility is the construction of fast, optoelectronic focal plane "Gabor" filters for optical data compression [21,2]. Thus, photoneural systems involving a few layers of LPNC processing are a feasible and potentially useful means for accomplishing a variety of pre-processing image transformations in computer vision. In a sense, such simple systems could function as fast, sensitive, simple and compact artificial retinas!

Assessment of the potential utility of larger scale photoneural systems is, at the moment, a matter of pure speculation. However, given the availability of LPNC arrays, more complex cognitive processes would be relatively uncomplicated to model and fascinating to study in an exploratory mode.

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