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Properties and applications of optical thyristors

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Abstract. — The optical thyristor is a promising device for optical information processing. It combines a receiving-, transmitting- and memory function in a single device, with at the same time a considerable optical gain. We show in this paper the dynamics of differential switching, i.e., the switching of a single thyristor in an array of thyristors, and compare it to the switching of a single device. We also review the recent developments which have led to a dramatic increase of the speed and optical sensitivity of optical thyristors. Finally, we show some interesting applications which have been realized with differential switching in arrays of sensitive thyristors (5×5 , 16×16 unto 32×64 devices), such as locating the maximum light intensity or integrated intensity of optical input patterns, and transcription of optical information from one thyristor array to another in free space.

1. Introduction.

Computing science evolves in the direction of conceiving parallel electronic computing systems. Unfortunately, the interconnection bottleneck seriously limits the increase of performance achievable with parallel processing. Massive optical interconnects could solve this bottleneck. Even more promising can be the realization of certain functions, like memorization, shifting and logical AND/NAND/OR/NOR done in a parallel optical way, using arrays of smart pixels.

The optical thyristor, usually implemented as a double-heterojunction PnpN structure in the GaAs/AlAs material system, is a bi-stable optoelectronic switch. The family comprises the DOES [1, 2], the VSTEP [3], the pnpn optical switch [4], the DHOT [5], and devices consisting of the vertical integration of an LED (or laser diode) and a heterojunction bipolar transistor, such as the LED-HPT [6], the LD-HPT [7], and the LAOS [8]. In the off-state, these latching devices have a high impedance, while in the on-state, they are conductive and, like an LED, emit light perpendicularly to the surface. Because of their versatility, they are currently considered to be candidate switches for parallel optoelectronic information transmission and processing, and memorization. Indeed, they combine the following assets : 1) they switch from the off-state to the on-state when they receive an optical [1] or electrical [2] input ;

2) they are active devices : the output light is generated, rather than being derived from the input light (this property is fundamental for cascaded logic operations in subsequent layers) ; 3) they memorize their on-state ; 4) smart pixels can be constructed with them for implementing logic functions ; 5) they are relatively simple to integrate into arrays.

The above-described versatility is a requirement for an optoelectronic switch, but it is not sufficient. Following parameters are of prime importance for a switch to be competitive : 1) the optical input energy required for switching from the dark off-state to the light-emitting on-state ; 2) the optoelectronic conversion efficiency — which determines the electrical power necessary for the required fan-out ; 3) the switch-on speed and the switch-off speed.

In the present paper, we give an overview of recent research efforts which have pushed the optical thyristor towards low energy and high speed. We will also demonstrate some applications which have to date been realized.

2. The optical thyristor.

Optical thyristor layers are grown by Molecular Beam Epitaxy. The layer sequence is n-p-n-p or p-n-p-n. A typical device structure is shown in figure 1. Starting from a p-type GaAs wafer, a 1 μm heavily p-doped buffer layer is grown, followed by :

- P : 500 nm $3 \times 10^{17} \text{ cm}^{-3}$ p-doped (Be) $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$, called the P-emitter ;
- n : 60 nm n-doped (Si) GaAs called the n-base (it consists of 10 nm doped at $n = 6 \times 10^{18} \text{ cm}^{-3}$ and 50 nm doped at $n = 1 \times 10^{18} \text{ cm}^{-3}$) ;
- p : 300 nm p-doped (Be) GaAs called the p-base (it consists of 280 nm doped at $p = 1 \times 10^{17} \text{ cm}^{-3}$ and 20 nm doped at $p = 1 \times 10^{18} \text{ cm}^{-3}$) ;
- N : 250 nm $2 \times 10^{17} \text{ cm}^{-3}$ n-doped (Si) $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$, called the N-emitter, capped by a 140 nm contact layer of n^+ -doped (Si) GaAs.

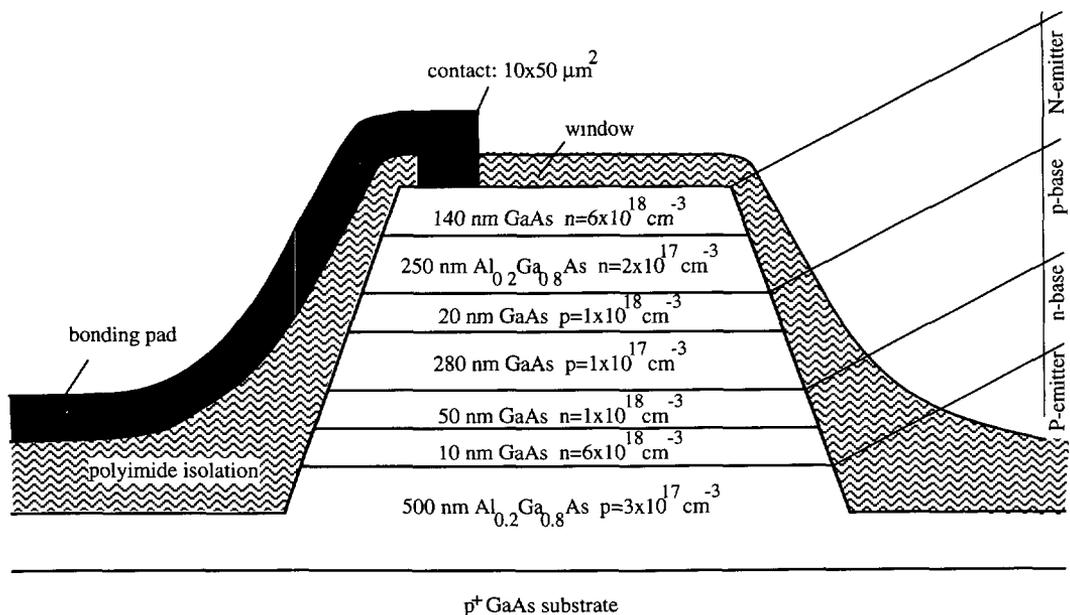


Fig. 1. — Cross-section of a typical processed PnpN device.

The tolerance on the layer thicknesses and doping concentrations is typically 20 %, such that basically all devices processed on a 2-inch MBE-grown wafer but those on the outer half cm satisfy the specifications.

Mesas of several sizes ($30 \mu\text{m} \times 30 \mu\text{m}$ up to $100 \mu\text{m} \times 200 \mu\text{m}$) and $1.16 \mu\text{m}$ high are obtained by wet etching in a 3 : 1 : 50 solution of $\text{H}_3\text{PO}_4 \cdot \text{H}_2\text{O}_2 : \text{H}_2\text{O}$. Their top (cathode) contact is a pad of AuGe/Ni/Au obtained by lift-off, that leaves an optical window over the remainder of the mesa surface. The quasi static electrical characteristics of such device are shown in figure 2. Pairs and arrays of such elements are obtained on chip by connecting the top-contacts in the processing cycle.

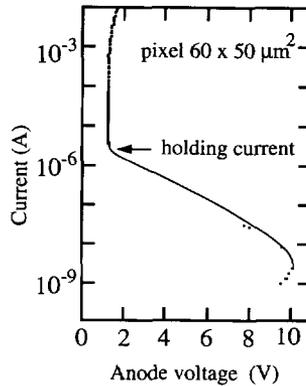


Fig. 2. — Current-voltage characteristics of the device of figure 1, with mesa area of $50 \times 60 \mu\text{m}^2$.

3. Switching principles.

Several switching principles can be used, leading to a different optical input sensitivity, a different functionality, and a different switching behavior.

3.1 QUASI STATIC SWITCHING. — In figure 3, the classical set-up is shown for an optically switched photo-thyristor. This is also the way three-terminal Si-thyristors normally operate. The thyristor is connected in series with a load and a power supply. The voltage is increased up to V_s . The voltage ramp must be *slow*, such as to avoid unwanted triggering of the thyristor to its on-state — a well-known phenomenon known as dV/dt triggering [9]. The thyristor is then in its off-state, at V_s (smaller than the breakover voltage V_{br}). When a light pulse, containing sufficient energy, impinges on the device, the breakover voltage lowers, and the device switches on. If made in III-V, the device emits light in this on-state. In the on-state, the current I is several orders of magnitude larger than in the off-state, and since the light-output is (to a first approximation) proportional to this current, a very high on-off contrast ratio can be obtained ($10^2 \dots 10^6$). The main advantage of this switching principle is that the operation is asynchronous. The most important drawback is that for obtaining a high sensitivity for optical inputs, V_s must be chosen very close to V_{br} , hence the time necessary to increase the voltage unto V_s without dV/dt triggering is prohibitively long (milliseconds).

3.2 DIFFERENTIAL SWITCHING. — One can try to make use of the fast dV/dt triggering to one's own advantage. To this end, two or more optical thyristors are connected in parallel, with a common external resistance R_c (Fig. 4a). The supply voltage V_s is ramped fast, such that one

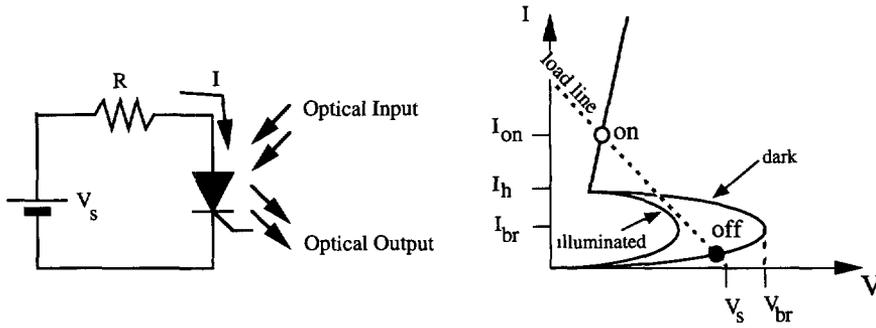


Fig. 3. — Quasi static switching of an optical thyristor.

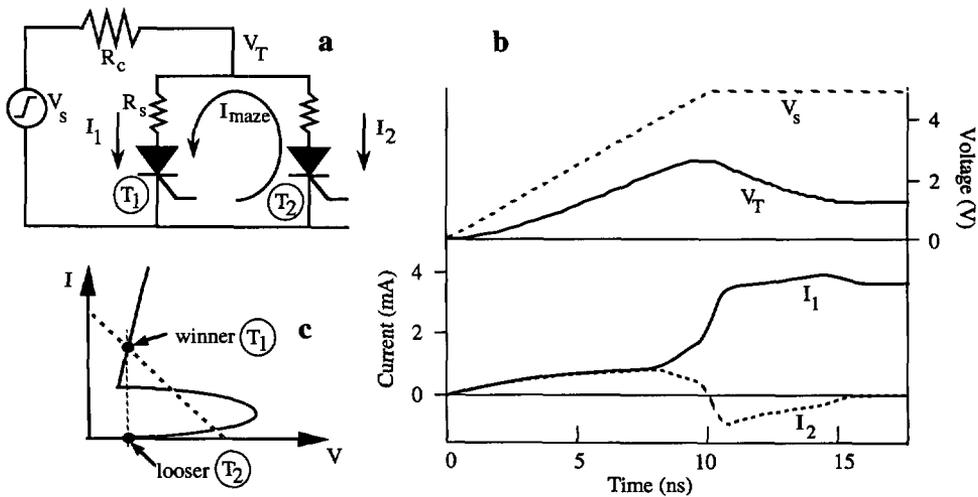


Fig. 4. — Differential switching of a thyristor pair : a) set-up and definition of the symbols ; b) calculated response of the circuit ; c) final state.

thyristor switches on by dV/dt triggering. Each thyristor tends to switch at a slightly different speed, due to small differences between the different thyristors. The first thyristor to switch on prevents the switching of all competitors. Indeed, as thyristor T_1 starts switching in figure 4, it forces V_T to decrease (at 10 ns in Fig. 4b), such that a maze current flows from T_2 to T_1 , discharging T_2 to the profit of T_1 . The current I_1 can then be seen to increase rapidly, while I_2 drops. The final state is shown in figure 4c : T_1 is « on » while T_2 is « off ».

Two thyristors tied together in this manner are called a *differential pair*. The on-state of one of the thyristors is associated to boolean « 0 », and the on-state of the other to boolean « 1 ». If there is no optical precharge, and if the two thyristors are very much alike (e.g. when they are neighboring elements on the same wafer) the winner is randomly chosen. However, a very small optical precharge suffices to decide upon the winner in the pair. The use of a differential pair has major advantages over the use of a single thyristor. Firstly, it is several orders of magnitude more sensitive to optical inputs than switching a single thyristor. Hara *et al.* reported differential switching with a resolution of 0.1 nW [10] and 400 fJ [11]. The second important advantage is that no critical biasing is required, neither optically nor electrically.

Due to this and to the fact that the switching is induced electrically, there is no critical-slowness-down phenomenon, i.e., no trade-off between switch-on speed and optical sensitivity [11]. A third advantage is that the boolean information is transmitted in dual-rail code, i.e., the thyristor pair emits a signal for the transmission of both a « 0 » and a « 1 ». This is known to strongly improve the bit-error rate for the transmission. A draw-back of using a differential pair is that some type of electrical clocking is needed.

The parallel set-up of more than two thyristors is called a *Winner-Takes-All* network [12]. Such network can be used to find the maximum light intensity of an input light pattern, as described further.

4. Improvement of the optical sensitivity by low emitter doping.

The optical sensitivity of optical thyristors depends on the doping concentrations of the emitter layers and of the base layers. For small anode currents, the base current of each bipolar transistor of the two-transistor equivalent model of a thyristor [9] is dominantly determined by the surface recombination current [13] at the perimeter of the mesa within the space charge region between each emitter and base. Although the pinning of the Fermi level at the surface reduces the effective barrier height at the surface, for small emitter-base voltages V_{EB} [14] this surface recombination current can still be expressed by the well-known formula [15] :

$$I_{\text{surf, rec}} \approx \frac{1}{2} q P S n_i \Delta W \exp \left(\frac{q V_{EB}}{2 k T} \right) \quad (1)$$

where P is the mesa perimeter, n_i is the intrinsic concentration and ΔW is the width of that portion of the space charge region where the maximal recombination occurs — smaller than the complete space charge region [14]. Because of the pinning of the Fermi-level at the surface, S is an « effective » surface recombination velocity ($\approx 10^7$ cm/s). Equation (1) assumes the recombination to occur over ΔW at maximum rate, i.e. at the rate that is reached when the electron and hole concentrations are equal. This rate is in fact only reached on one contour line (around the mesa) of the space charge region. Analogously to the reduction of the bulk recombination in the space charge region [16], it is crucial to position this contour line in the wide-bandgap material, because n_i , and therefore the recombination current, is then much smaller.

In our devices, 80 to 95 % of the emitter-base space charge region is located in the (wide bandgap) emitters, because the emitter doping is 5 to 20 times smaller than the adjacent base doping. ΔW is therefore located in the wide bandgap layers, and the surface recombination currents are thus reduced. To demonstrate the improvement of using such low emitter doping to increase the optical sensitivity, we measured simple bipolar heterojunction transistors (HBT). Figure 5 shows the DC amplification β of the photo-generated current of a normal bipolar Npn transistor (with $N_{\text{emitter}} = 10^{18} \text{ cm}^{-3}$ and $N_{\text{base}} = 2 \times 10^{17} \text{ cm}^{-3}$), and of an Npn transistor with lightly doped emitters (with $N_{\text{emitter}} = 10^{17} \text{ cm}^{-3}$ and $N_{\text{base}} = 10^{18} \text{ cm}^{-3}$) for several optical inputs. An identical current amplification is reached at a 1 000 times smaller current level in the case of low emitter doping.

As a result of this increase in gain of the two transistors inside the thyristor, our optical thyristors have a low holding current (0.2 to 2 μA), the lowest reported for thyristors with no mesa-passivation. The improved gain at low current levels thus obtained makes these thyristors more sensitive to input light. This method of dealing with the surface recombination has the obvious advantage that the performance of the thyristors does not degrade with time, which is a concern when mesa-passivation techniques [17, 18] with dubious long-term stability are used.

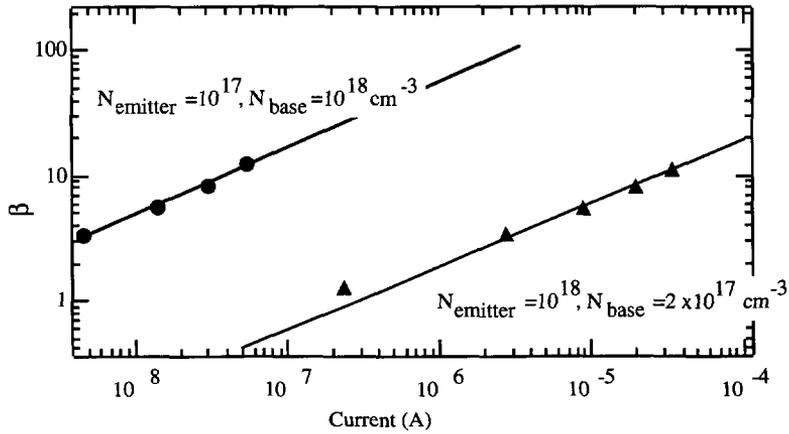


Fig. 5. — Measured gain (= collector current/photo-generated current) of two Npn transistors *versus* the collector current. To obtain the same gain β , a three orders of magnitude smaller current is needed when the emitter is doped significantly less than the base.

The improvement in the optical sensitivity obtained with this technique allows cascadable optical switching. This means that a thyristor can be switched on by illuminating it with the light of a similar device. In figure 6, the current characteristics of a thyristor are shown for several values of the incident optical power *generated by an identical thyristor*. It is clear that a thyristor can easily be switched when illuminated by a twin device.

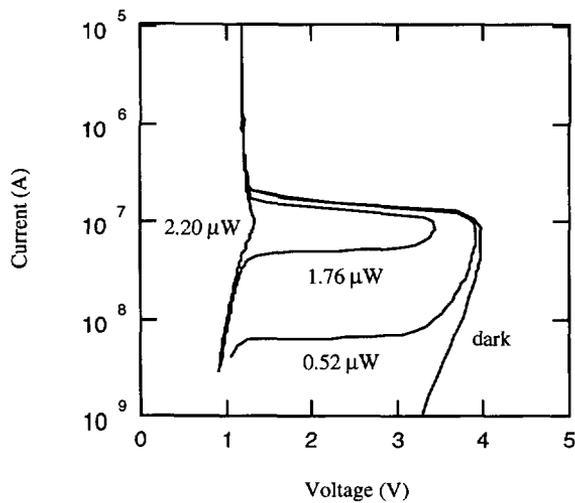


Fig. 6. — Current-voltage characteristics of a thyristor (with $110 \times 55 \mu\text{m}^2$ mesa and $100 \times 35 \mu\text{m}^2$ window) at several optical inputs *generated by an identical thyristor*

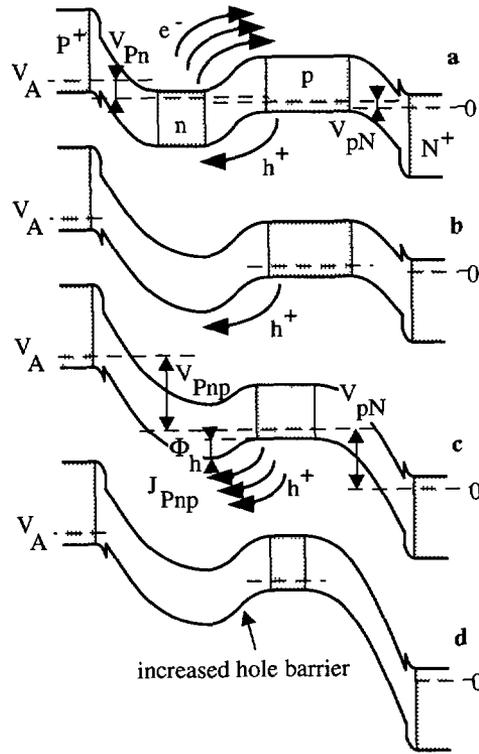


Fig. 7. — Majority carrier extraction from a thyristor by means of a negative anode-to-cathode voltage pulse : a) electron extraction from the n-base ; b) reach-through ; c) hole extraction from the p-base ; d) quasi-steady-state.

5. Depletion of the base layers for improvement of speed and optical sensitivity.

Thyristors are ill-reputed for having a slow turn-off speed [9]. The origin of the turn-off problem is as follows. In its on-state, a PnpN structure has three forward-biased junctions. When the bias is pulsed to zero, the sum of the biases over the P-n, the n-p and the p-N junctions is forced to zero, but not the individual values of these biases. The equilibrium state, with three zero-biased junctions, is reached by self-discharge of the junctions, which is a very slow process (typically milliseconds). As long as equilibrium is not established, the two center thyristor layers (n and p) contain more majority carriers than at equilibrium and as a consequence, the thyristor suffers from enhanced dV/dt triggering. In a single thyristor switch, this means that the voltage V_s has to be applied even slower than when starting from equilibrium. In a differential pair, it means that when the voltage is applied, the thyristor which was in the on-state during the previous cycle will switch on again, even if the light input is given to his neighbor. To avoid this, the light input, which generates carriers in the thyristor which is chosen to switch on, must be increased dramatically (such that the optically generated carriers in the intended winner can exceed the left-over carriers in the previous winner). The trade-off between cycle speed and optical sensitivity is therefore very poor.

To avoid this poor trade-off, the excess majority carriers of the center regions must be extracted before the light input is given. This has been tried by means of a third and fourth contact to the center thyristor layers [2, 19-21]. The processing technology then becomes

complex, and the presence of a third and fourth terminal jeopardizes the integration of such switches in arrays. An easier solution would be extract the carriers by applying a negative anode-to-cathode voltage pulse. When applying a negative anode voltage V_A , as shown in figure 7a, electrons from the center n-region are extracted faster than holes from the p-region, because the Npn transistor has the better gain. As only few of the slowly-diffusing holes are evacuated, the majority carrier charge that forward-biases the emitter-base junction of the better transistor when a positive anode voltage is applied is not much decreased, and this transistor still rapidly induces dV/dt switching. For this reason, attempts to use a negative voltage pulse to speed up the turn-off process have not been successful in the past [19].

Recently, a method has been proposed to overcome the above-described problem [5, 22]. It requires a PnpN device in which the n-type base layer can be completely depleted by reverse biasing the P-n junction, before this junction breaks down. For a negative anode voltage in excess of that necessary for the P-n and n-p space charge regions to meet each other through the n-layer (the « reach-through » condition, Fig. 7b), the thermionic emission current of holes from the p-layer increases dramatically, as the barrier Φ_h against hole emission is decreased (Fig. 7c). The time constant for the hole extraction is in practice RC -limited (R is the external resistance) and typically less than 10 ns [5]. In the final state (Fig. 7d), the amount of holes in the p-region can be sufficiently small for dV/dt triggering to be suppressed when the thyristor is switched to the on-state again.

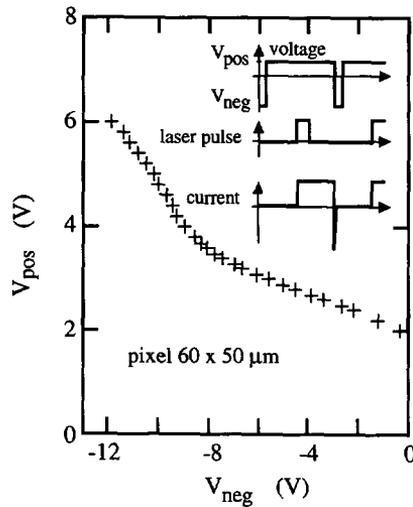


Fig. 8. — Turn-off characteristics for 30-ns turn-off pulses (V_{neg}).

The thyristor described in section 2 complies with the requirement that the n-layer can be depleted completely. The hole-extraction measurement is shown in figure 8. The turn-off was measured with the voltage pulse cycle (applied over 100 Ω) shown in the insert. After a negative pulse to V_{neg} for 30 ns, the voltage is increased in 10 ns to a certain positive value V_{pos} . The thyristor (kept at V_{pos}) is then switched on by illumination with 670-nm laser light. Then, the voltage is decreased in 10 ns to V_{neg} again. For each value of V_{pos} , there is a critical V_{neg} beyond which the thyristor does not switch on when the voltage is pulsed to V_{pos} . The current through the thyristor then only flows after triggering by the laser. The relation between each chosen V_{pos} and the corresponding critical V_{neg} is shown in figure 8. There is a

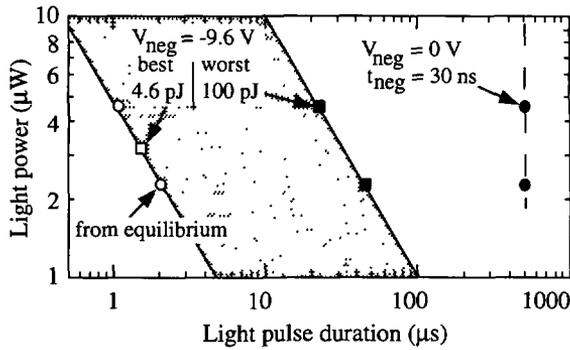


Fig. 9. — Optical energy for *cascaded* operation of a differential pair in which the carriers are extracted between the cycles, as compared to the case when no carrier extraction occurs.

rise of V_{pos} for V_{neg} in excess of the voltage necessary for punch-through of the n-layer (-8 V). For sufficient V_{neg} (-12 V), the thyristor can abruptly be switched to a reasonably high voltage (6 V) before dV/dt triggering occurs. This shows that hole extraction from the center layer has been realized.

When such thyristors are tied in a differential pair, fast and sensitive cascable operation is expected. Consider a differential pair of thyristors, one of which is in the on-state. The bias over the pair is pulsed (over $100\ \Omega$) for 30 ns to $V_{neg} = -9.6\text{ V}$, then brought to zero. An optical input, *originating from another thyristor*, then impinges on a random thyristor of the pair. Figure 9 shows the relation between the minimum duration and the power of this optical input for the correct thyristor of the pair to switch on when a bias $V_{pos} = 5.6\text{ V}$ is applied to the pair after the illumination. Depending on the exact history of the switching cycles, 4.6 to 100 pJ are shown to be required. This is to be compared to two extreme cases : if the 30-ns

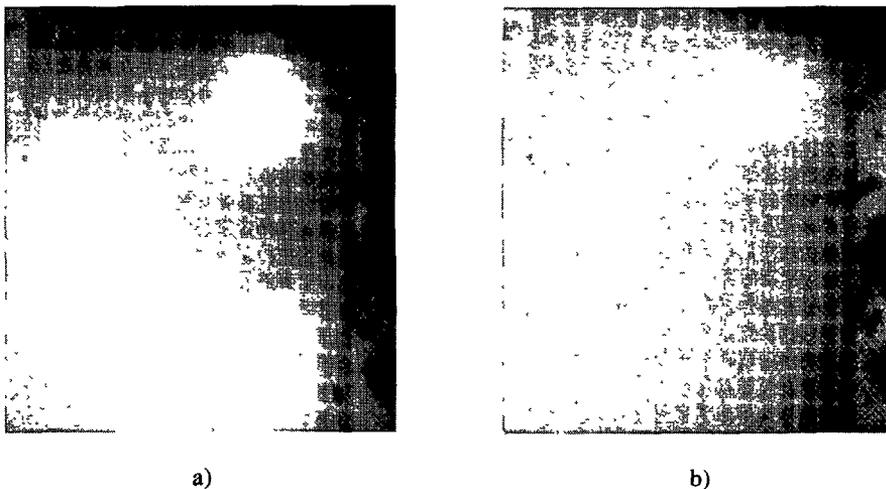


Fig. 10. — Top view of a monolithic 16×16 thyristor array, with total area of $775 \times 900\ \mu\text{m}^2$; a) a distributed 2-dimensional input light pattern is applied to the array ; b) after the voltage is switched on, competition leads to a fast and correct switch-on of the thyristor located at the maximum input light intensity. The winning pixel emits light.

turn-off pulse does not go negative but remains at 0 V, the minimum duration of the optical input pulse is 500 μs , and the minimum optical energy is more than 1 nJ ; if, on the other hand, both thyristors of the pair are in *equilibrium* (0 V) before the input pulse is applied to one of them, 4.6 pJ is necessary for correct switching.

In the above example, the absorption efficiency of the input light is only about 0.2 %, because of the fact that the light is generated by an identical thyristor as the receiving device. If input light with a shorter wavelength is used, the absorption can be increased easily to 20 %. The input light energy then also decreases by two orders of magnitude, i.e., it becomes 0.05 to 1 pJ.

A further dramatic reduction of the optical input energy is expected when thyristors are developed in which *both* the center n-layer and the center p-layer can be totally depleted [23]. Recent results with such thyristors have shown operation with femtojoule optical inputs at tens of MHz [24].

A final comment should be made concerning the electrical energy consumption corresponding to the above-discussed optical energy. The electrical energy dissipated by an LED or a thyristor generating the light intended to switch on another thyristor is about two orders of magnitude larger than the optical energy required for correct switching. With the most recent technological developments, we can estimate the external quantum efficiency of the light-emitter to be 30 % [25], and the power transmission of the optics to be at best 10 % (using an optical system with a numerical aperture of 0.6 or better). Also, the active device only dissipates a fraction (typically 30 %) of the total electrical power, the remainder being consumed in termination resistances. Hence, 0.1 pJ optical energy could correspond to 10 pJ electrical energy. This is very attractive when compared to the electrical energy required today for the transmission of one bit with an electrical interconnect, which is of the order of 250 pJ.

6. Applications.

6.1 MAXIMUM INTENSITY LOCALIZATION. — In several domains of optical parallel processing, like optical neural nets and pattern recognition, there is a need to identify the location of the maximum light intensity in a 2D spatially distributed light pattern. A monolithic array of 256 optical thyristors (16×16) connected in parallel can achieve this [26], using the Winner-Takes-All principle. Figure 10a shows a photograph of a 16×16 thyristor array, on which a distributed input light pattern is applied ; the result after application of a 6 V step in 20 ns is shown in figure 10b. The thyristor located at the place of the highest intensity has switched on, and emits tens of μWatts of light. The time span between the start of the voltage step and the end of the decision is 150 ns.

Instead of a permanent input light pattern, one can also apply an image during a certain time before applying the voltage. Figure 11 shows the measured differential resolution of the system. Two random pixels of the array of figure 10, called pixel A and pixel B, each receive an optical input pulse. Immediately after the optical input, the voltage step is applied. For all cases that pixel A receives an optical surplus of at least 80 pJ, only pixel A switches on. The same holds for pixel B. With smaller differences, the correct decision is not always made : sometimes, even both pixels switch on. Without light input a random pixel of the array wins, showing that all pixels are identical. Because of its inherent speed, this way of locating the maximum intensity in a plane can be useful in 4-f processing (this function is usually accomplished by a CCD-camera in combination with a personal computer), and for symbolic substitution.

6.2 MAXIMUM DOSE LOCALIZATION. — In the previous paragraph, an optical image is exposed on an array of thyristors connected in parallel at 0 V. Then a voltage step is applied,

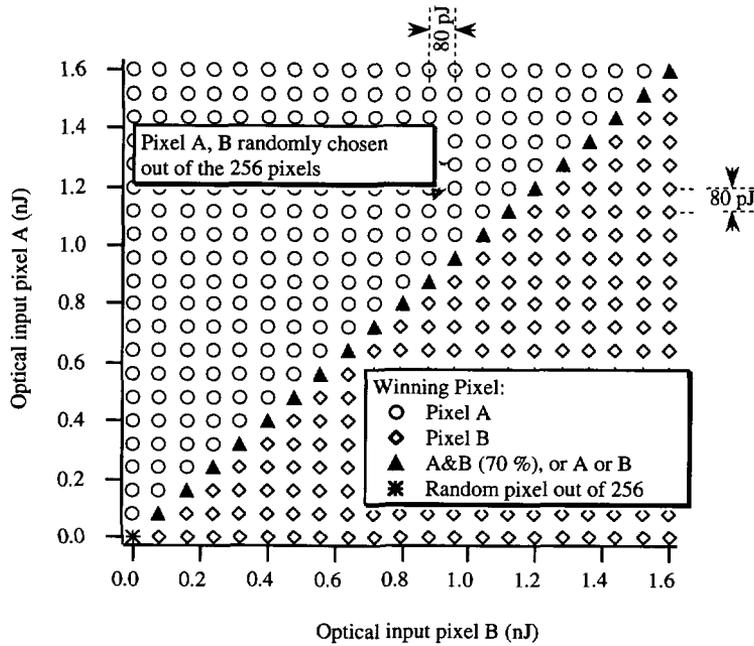


Fig. 11. — Optical energy incident on a pixel A *versus* optical energy on pixel B ; the difference in optical energy must at least be 80 pJ for correct switching, otherwise it is possible that both pixels switch on.

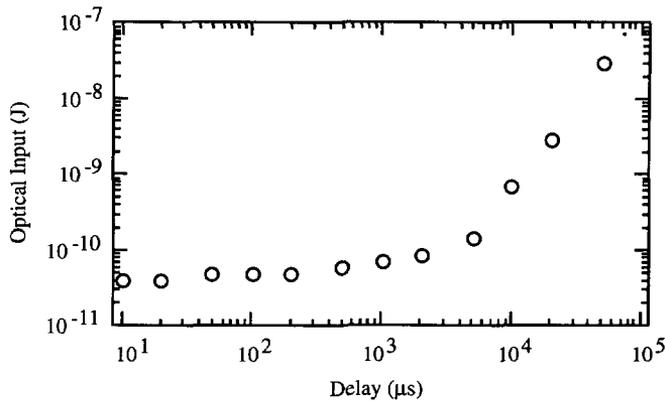


Fig. 12. — The minimum optical energy necessary to reliably switch the illuminated pixel as a function of the time delay between this optical pulse and the application of the voltage step.

and a winner pops up. In order to demonstrate *optical dose* integration, similar experiments were made [26] with a variable time delay between the optical input and the application of the voltage step. One would expect that the optically induced precharge would leak away during such a delay time, so that the required minimum optical energy with delay would be larger. Indeed, for delays longer than 1 ms, much larger optical pulses are needed (Fig. 12). However, for delay times smaller than 1 ms, the minimum optical input energy varies slowly (between 40 and 70 pJ).

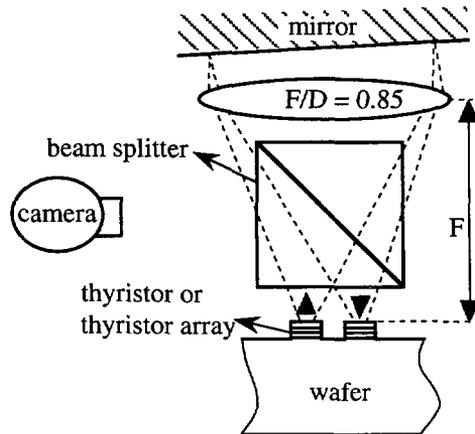


Fig. 13. — Set-up used to obtain a mirrored image from one thyristor or thyristor array on another. The beam splitter is for obtaining an image on the CCD camera.

This means that, to a first approximation, all optical energy incident on the pixel within 1 ms before the application of the voltage step is integrated. This is true for all pixels of the array, so that the maximum optical dose can be localized. For arrays where no care was taken to avoid surface recombination using the low emitter doping described in section 4, maximum localization is not possible, because the integration time is too small.

6.3 ARRAY TO ARRAY TRANSCRIPTION OF OPTICAL INFORMATION. — We show the possibility to transcribe optical information from one array to another [27]. The set-up of figure 3 is used to image each pixel of one array onto the corresponding pixel of another array on the same wafer. We use monolithic arrays of 5×5 elements, in which every thyristor has an own resistance of about 7Ω . Due to this relatively large resistance, the thyristors are less tightly tied together than in a normal winner-takes-all array. As a result, the competition between the pixels, which determines the winner, can be attenuated, and this permits to force more than a single thyristor of the array to switch to its on-state. When a voltage step to 16 V in 20 ns over 100Ω common resistance is applied to the array, up to 4 pixels of the 25 can be switched on. The on-state of these four optical thyristors of the left array can then be transferred to the neighboring array by applying an analogous voltage step on the receiving array. Figure 14 shows the result of the image transcription.

7. Conclusions.

We have demonstrated that optical thyristors are promising optoelectronic switches. They can be engineered for fast operation and high optical sensitivity. Operation with 10 femtojoule optical inputs at 100 MHz can reasonably be expected to be demonstrated in the near future. Cascadable operation has been demonstrated, as well as fan-out. Therefore, the switches are not only promising for optical information transmission, but also for optical processing. Furthermore, arrays of specially conceived thyristors show interesting functionalities, such as localization of the maximum intensity and dose of an input pattern or image, and the possibility to transcribe optical information from array to array.

Further research is oriented towards reducing the required optical energy, increasing the speed, and improving the cascability. Attention is also paid to the fabrication of smart pixels with thyristors.

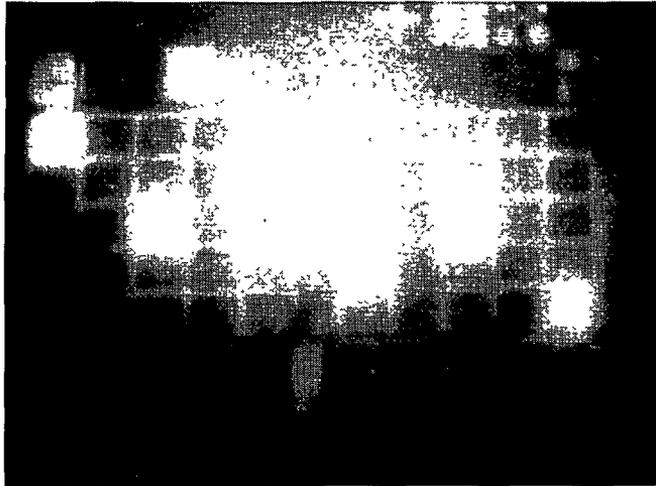


Fig. 14. — Photograph of two neighboring arrays. The right array has copied mirrored information (four pixels) from the left array with the dV/dt triggering scheme.

Acknowledgments.

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