Filename outline 2000.wpd

Worksheet for CY 2000 R&D 100 Entry Form

A. Charge number 3435-0013

B. Funding source LDRD and DARPA

Did LDRD ever fund this work? Yes, presently optical switching is being directly funded and previously the fundamental mechanism was investigated indirectly related to optical switching.

C. Point of contact

Name: S. Rajic
Telephone: 423-574-9416
Email: rajics@ornl.gov

The following list contains the questions specified by the staff at *R&D Magazine*. Please answer questions 3 through 12 and 15. If you are filing a joint entry, please also complete question 2.

1. Submitting organization
Organization name: Oak Ridge National Laboratory
Address: P.O. Box 2008
City: Oak Ridge
State: TN
Zip code: 37831-6255
Submitter's name: Alvin W. Trivelpiece
Phone: 865-576-2900
Fax: 865-241-2967
Email: trivelpiecaw@ornl.gov

2. Joint Entry with . . .

Organization name: Environmental Engineering Group
Address: 11020 Solway School Rd., Suite 109
City: Knoxville
State: TN
Zip code: 37931
Submitter's name: Irene Datskou
Phone: 865-927-3717
Fax: 865-927-3817
E-mail:eeg@vic.com

3. Optically Actuated Photonic Switch (OAPS)

4. Briefly describe (25 words or less) what the entry is (e.g., balance, camera, nuclear assay, etc.)

Optical switching by micro-mechanical movement induced by optical absorption of the waveguide material by photons above the energy bandgap disrupting an evanescent field across a small physical gap.

5. Product Availability

a. First available for licensing 3/26/99 (Received at US Patent office)

b. Is the product licensed? No

c. Is this entry a resubmission? No

6. Inventor or principal developer

Developer name: Slobodan Rajic
Position: Development Staff Member
Organization: Oak Ridge National Laboratory
Address: P.O. Box 2009, MS-8039
City: Oak Ridge
State: TN
Zip code: 37831
Country: USA
Phone: 423-574-9416

Fax: 423-574-9407
Email: rajics@ornl.gov

Developer name: Panagiotis G. Datskos
Position: Development Staff Member
Organization: Oak Ridge National Laboratory
Address: P.O. Box 2009, MS-8039
City: Oak Ridge
State: TN
Zip code: 37831
Country: USA
Phone: 423-574-6205
Fax: 423-574-9407
Email: pgd@ornl.gov

Developer name: Charles M. Egert
Position: Development Staff Member
Organization: Oak Ridge National Laboratory
Address: P.O. Box 2009, MS-8039
City: Oak Ridge
State: TN
Zip code: 37831
Country: USA
Phone: 423-574-9410
Fax: 423-574-9407
Email CME@ornl.gov

Developer name: Irene Datskou
Position: President
Organization: Environmental Engineering Group
Address: 11020 Solway School Rd., Suite 109
City: Knoxville
State: TN
Zip code: 37931
Country: USA
Phone: 865-927-3717
Fax: 865-927-3817
Email eeg@vic.com

7. Product price

MEMS based devices rely on microelectronics fabrication methods, thus the price is highly dependant on volume. Also complicating the question is that in most implementations a network of switches would be employed unlike the several devices per wafer that a national laboratory would fabricate. A nominal value of $100 would be required for many implementations.

8. Patent Status

a. Do you hold any patents on this product? No

b. Do you have any patents pending on this product? Yes
Received at US Patent office on 3/26/99 (pending), ORNL ERID 612

9. Describe your product's primary function as clearly as possible in one page. What does it do? How does it do it? What theories, if any, are involved?

Micro-optical switching is a very technically challenging area. The technologies employed or investigated to date are compromise designs. The four basic parameters that are often traded against each other are optical throughput / rejection efficiency, cost, speed, and size. Although one or more of these parameters can be optimized satisfactorily, there is not an approach to date that totally satisfies the three main applications communities. We believe our approach is superior to the presently known techniques and would be applicable in fiber-optic communications, integrated optic sensors, and especially optical computing.

We have developed a new approach for micro-optical switching using photo-induced deflection in micro-mechanical beams / waveguides. The approach uses the mechanism that is based on the conversion of photons to "free" charge carriers in a semiconductor, which in turn, gives rise to a photo-induced stress. The photo-induced stress is manifested as an increase (or decrease) in the lattice constant of the semiconductor crystal. If an appropriately thin micro-structure waveguide is used, the photo-induced stress can be detected as a change in the radius of curvature and therefore in the displacement of the thin waveguide. Small changes in displacement are routinely measured in atomic force microscopy (AFM) where atomic imaging relies on the measurement of changes ($<< 10^{-9}$ m) in the bending of micro-mechanical beams.

Photons impinging on a semiconductor can generate charge carriers in a very short time (<ns)

resulting in a rapid response time. Furthermore, this mechanism does not rely on changes in the temperature of the device, and therefore thermal effects can be neglected if the micro-device is well heat sunk. The equation below describes the photo-induced and thermal effects

$$?s \;'\; ?s_{pi} \% ?s_{th} \;'\; \left(\frac{1}{3} \frac{d g_g}{dP} ? n \right) E \;\%\; a ? T E \qquad \textbf{(1)}$$

represented as term 1 and term 2 of the equation, respectively. This high speed effect in comparison to the slow thermal effect can be seen in the data in figure 1. Figure 2 illustrates the expansion or contraction of the crystal waveguide material resulting from the sign of the pressure dependance of bandgap energy term in equation 1. Utilizing such a mechanism we have constructed such devices using materials with various bandgap energies. Silicon was also an obvious choice since it can be readily fabricated and such a waveguide could transmit important signal wavelengths such as 1.3 and 1.55 micrometers while the photo-induced deflection could be initialed with an orthogonal 0.85 micrometer source. The coupling / rejection efficiency of this type of device is high due to the proximity of the bisected waveguide segments such that the evanescent field is involved in the coupling. Additionally, anti-reflection sub-wavelength structures are used to achieve high throughput. Figure 3 illustrates this modulation / switching concept. Figure 4 shows the waveguide microstructure devices.

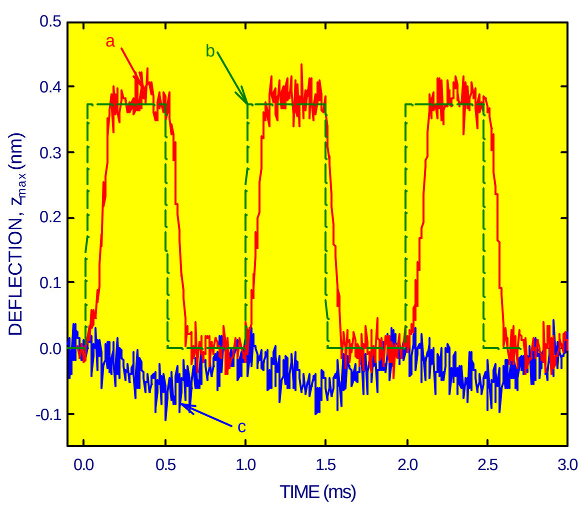

Figure 1. Curve (b) represents the modulation frequency. Curve (a) represents the photo-induced deflection due to the absorption of photons above the material bandgap energy and thus generation of carriers. Curve (c) represents the thermal response during illumination by photons below the bandgap energy. Note the sluggish thermal response and opposite deflection direction compared to the photo-induced case.

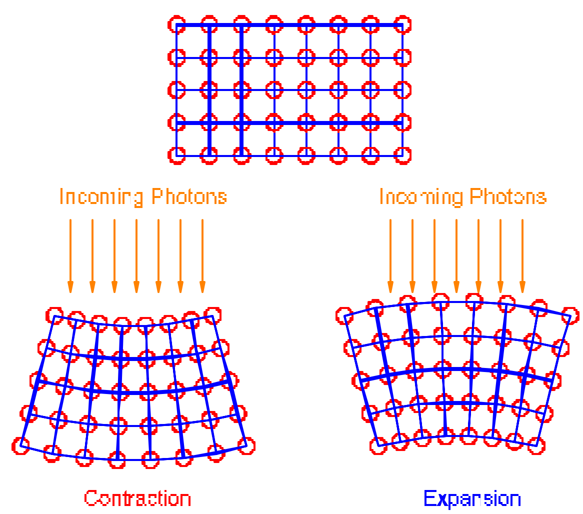

Figure 2. Depiction of a silicon crystal lattice when exposed to photon energies both above and below the material bandgap. Most materials expand regardless of the input photon energy.

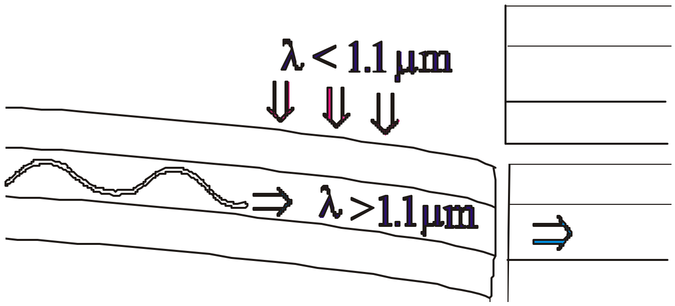

Figure 3. The all optical switching concept is illustrated in a silicon waveguide two position switch. Photons above the bandgap energy are absorbed and stress the crystal waveguide material thus controlling the flow of the orthogonal signal photons which have energies below the bandgap.

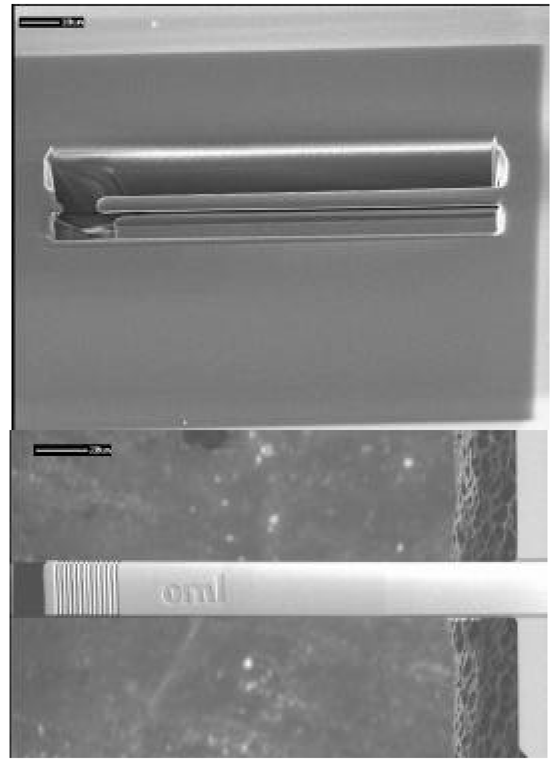

Figure 4. Shown above are the initial feasibility microstructure and the most recent waveguide device.

10. Competitors

a. List your product's competitors by manufacturer, brand name, and model number.

The optically actuated optical switching mechanism could be applied to several specific applications. The most exciting implementation is as an essentially all-optical transistor, with perhaps more impact than the original electronic version due to the tremendous advantage of photons over electrons. This advantage is now being exploited in the fiber-optic telecom industry were relatively few optical switches are required. However for optical computing application there is presently no existing alternative. Thus there are no commercial computers presently based on the photon. The mechanisms examined, to date, have typically been demonstrations (not products) by either academia or telecom organizations.

b.

Table 1	***Classification of Optical Waveguide control***	
Interaction	***Effect***	***Phenomenon***
MEMS / Light	Photo-Induced Stress	Evanescent Field Coupling
Elec.-Field / Light	Electro-Optic	Index Change
Sound / Light	Acousto-Optic	Index Change
Mag.-Field / Light	Magneto-Optic	Polarization Rotation
Heat / Light	Thermo-Optic	Index Change
Light / Light	Nonlinear-Optic	Induced Polarization

c. Describe how your product improves upon competitive products or technologies. Be specific. Include such items as how much faster, how much less cost, etc.

We simultaneously maximize all four important parameters: optical throughput / rejection efficiency, cost, speed, and size in an all optical configuration (photons controlling the propagation of other photons). The mechanisms employed to date have typically been demonstrations (not products) by either academia or telecom organizations. These demos have not yielded the properties required for a practical optical switch such as an all-optical transistor. The classification of these methods is summarized above in table 1. Interferometry based approaches have been attempted with moderate efficiency, relatively high cost and the device size limited very large scale integration. The most often attempted schemes involved an index of refraction change induced by an electro-optic, acousto-optic, or thermo-optic effects. Certain approaches have produced impressive results for a given parameter, such as speed, however it has always been at the expense of other required parameters such as size, efficiency, cost and even input power. The only approaches that have been even moderately realistic employ integrated waveguide devices. However even this technology has not proven itself commercially. A list of references is provided below:

1. A. Marrakchi, W.M. Hubbard, and S.F. Habiby, Review of photonic switching device technology, *Coherent Optical Communications and Photonic Switching*, G. Prati, editor, pp. 299-312, (1990)

2. S. Nakamura, K. Tajima, and Y. Sugimoto, "Experimental investigation on high-speed switching characteristics of a novel symmetric mach-zehender all-optical switch", *Applied Physics Letters*, Vol. 65(3), pp. 283-285, (July 1994).

3. H. Avramopoulos, P.M.W. French, M.C.Gabriel, H.H. Houh, N.A. Whitaker Jr., and T. Morse, "Complete switching in a three-terminal sagnac switch", *IEEE Photonics Technolgy Letters*, Vol. 3(3), pp. 235-237, (Mar. 1991).

4. M. Haruna and J. Koyama, "Electro-optical branching waveguide switches and their appication to 1X4 optical switching networks", *IEEE J.Lightwave Tech*.,LT-1(1) 223-227, (Mar. 1983).
5. J.E. Zucker, K.L. Jones, T.H. Chiu, B. Tell, and K. Brown-Goebeler, "Strained quantum wells for polarization-independant electro-optic switches", *IEEE J.Lightwave Tech*., Vol.10(12), pp. 1926-1930, (Dec. 1992).
6. T. Morioka, and M. Saruwatari, "All-optical ultrafast nonlinear switching utilizing the optical Kerr effect in optical fibers", *SPIE Optical Engineering*, Vol. 29(3), pp. 200-209.
7. M. Haruna, *Optical Devices & Fibers*, Sec. 2.2 Thermo-optic waveguide Devices, JARECT, Vol. 17(Y. Suematsu, ed.) Tokyo, Ohmsha, Ltd., and North-Holland Pub. Co., 1985
8. S.R. Friberg, A.M. Weiner, Y. Silberberg, B.G. Sfez, and P.S. Smith, "Femtosecond switching in a duel-core-fiber nonlinear coupler", *OSA Optics Letters*, Vol. 13(10), pp. 904- 906.
9. T. Toshio, M. Ogawa, H. Inoue, S. Nishimura, and K. Ishida, " Lossless and low crosstalk InP based 2X2 optical switch with integrated optical amplifier", *OSA Proceedings on Photonics Switching*, Vol. 16, pp. 42-46, (1993)
10. W.J. Smith, *Optical Integrated Circuits* , McGraw Hill, New York, 1985, p98
11. P. Datskos, S. Rajic, and I. Datskou, “Photoinduced and thermal stress in silicon micro-cantilevers,” *Appl. Phys. Lett*. 73, 2319-2321 (1998).

11. Applications

The major application for this technology is as an “optical transistor” for optical computing. Opportunities also exist for direct optical switching in fiber-optic telecommunications and as modulators or sensing elements in integrated optics sensors.

12. State in layman’s terms why you feel your product should receive an R&D 100 Award. Why is it important to have this product? What benefits will it provide?

Efficient, low-cost, fast, and large scale integration of an all optical switch/transistor will revolutionize computing much as fiber-optic implementation has revolutionized the telecommunications industry. Numerous advantages belong to the photon over the electron in an optical transistors such as providing substantially more information throughput, due to the fact that multiple wavelengths can propagate along the same conductor each carrying more information than its metal counterpart. Cross conductors are also possible since photons can not “short out” if two cross conductors touch. The light waves will interact locally but each will continue unabated. This will provide for greater scales of integration since intermediate insulating layers are not required.

13. Chief executive officer

Name: Alvin W. Trivelpiece

Position: President
Organization name: Oak Ridge National Laboratory
Address: P.O. Box 2008
City: Oak Ridge
State: TN
Zip code: 37831-6255
Phone: 865-576-2900
Fax: 865-241-2967
Email: trivelpiecaw@ornl.gov

14. Contact person to handle all arrangements on exhibits, banquet, and publicity
Name: Ronald A. Walli
Position: Research and development writer
Organization name: Oak Ridge National Laboratory
Address: P.O. Box 2008
City: Oak Ridge
State: TN
Zip code: 37831-6266
Phone: 865-576-0226
Fax: 865-417-5390
Email: wallira@ornl.gov

15. To whom should reader inquiries be directed?
Name: Slobodan Rajic
Position: Development Staff Member
Organization name: Oak Ridge National Laboratory
Address: P.O. Box 2009, MS-8039
City: Oak Ridge
State: TN
Zip code: 37831
Phone: 423-574-9416
Fax: 423-574-9407
Email: rajics@ornl.gov