IEEE
CHARGE-COUPLED DEVICES
WORKSHOP
(1991)

final program

June 7-9, 1991
Held at the
University of Waterloo, Waterloo
Ontario, Canada N2L 3G1

Sponsored by:

IEEE Kitchener-Waterloo Section

Information Technology Research Center (ITRC)

Natural Sciences and Engineering Research Council (NSERC)

Institute of Computer Research (ICR)
University of Waterloo

Department of Electrical and Computer Engineering
University of Waterloo

ORGANIZATION DETAILS
1991 Steering and Technical Program Committee

Savvas G. Chamberlain (Chairman of CCD Workshop)
Professor
Electrical and Computer Engineering Department
University of Waterloo
Waterloo, Ontario N2L 3G1, Canada.
Tel: (519) 888-4598 Fax: (519) 746-6321

Eric R. Fossum
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109.
Tel: (818) 354-3128 Fax: (818) 393-0045

Marvin H. White
Sherman Fairchild Professor
Electrical Engineering Department
Lehigh University
Bethlehem, Pennsylvania 18015.
Tel: (215) 758-4421 Fax: (215) 758-4561

Arokia Nathan
Assistant Professor
Electrical and Computer Engineering Department
University of Waterloo
Waterloo, Ontario N2L 3G1, Canada
Tel: (519) 888-4803 Fax: (519) 746-3077

WELCOME REMARKS

On behalf of the Steering and Technical Program committee I like to welcome you to Waterloo. Our CCD workshop is truly an international meeting. We have participants from Europe, Japan, USA, Canada and other countries. Our facilities can accommodate 80 to 100 participants, we are close to this limit.

As you may have noticed we changed the format and theme of the workshop this year. The workshop covers the advances in the theory, design and fabrication of CCD's which are applied for silicon image sensors, silicon and GaAs signal processing, and HDTV.

The purpose of our workshop is the dissemination of fundamental research material which is already published or to be published but is non proprietary, including models and design techniques applied to the advancement of the theory and design of CCD Image Sensors and GaAs devices. The applications of these sensors include, visible and near infra red imaging, signal processing, scientific HDTV, still cameras and other applications.

Speakers are allowed of up to 50 minutes to go into in-depth description and analysis of their subject. We have fifteen workshop talks. Each workshop lecture has a high intellectual, technical and scientific content.

Workshop lectures cover fabrication techniques, device theory, device design accompanied by quantitative and qualitative treatment of specific CCD subjects. Other lectures cover device modeling for two and three dimensional effects, fabrication process analysis, quantitative performance treatment and special design techniques.

Speakers provided an original copy of their slides or transparencies of their talk. These are copied and distributed to the participants of the workshop. If there is interest amongs the authors we may later on add text to these diagrams, edit these and possibly submitt it for publication in a book. If you are interested in this please let me know.

Finally, I like to thank all the authors and co-authors of the workshop, the participants and the sponsors which include;
IEEE Kitchener-Waterloo Section,
Electrical and Computer Engineering Dept. University of Waterloo,
National Science and Engineering Research Council (NSERC),
Institute of Computer Research (ICR) University of Waterloo,
Information Technology Research Center (ITRC).

During the CCD workshop, if you need any help in order to make your stay at the University of Waterloo more enjoyable please let us know.

Savvas G. Chamberlain
Chairman
IEEE CCD WORKSHOP (1991).

THEME OF THE WORKSHOP

The workshop is intended to cover the advances in the theory, design and fabrication of CCD's which are applied for silicon image sensors, silicon and GaAs signal processing, and other applications.

The purpose of this workshop is the dissemination of fundamental research material which is already published or to be published but is non proprietary, including models and design and fabrication techniques applied to the advancement of the theory and design of CCD Image Sensors and GaAs devices. The applications of these sensors may include, visible and near infrared imaging, signal processing, machine vision, scientific HDTV, still cameras and other applications.

Speakers will be allowed up to 50 mins. to provide an in-depth description and analysis of their subject. Each workshop lecture is expected to include high intellectual, technical, and scientific content.

Individual workshop lectures are expected to include and cover quantitative and qualitative description, device theory, device design accompanied by quantitative models or equations of their subject. Other lectures would cover device modeling for two and three dimensional effects, fabrication process and analysis, quantitative performance treatment and special design techniques.

LOCATION

The conference will be held at the University of Waterloo which is about 90 km (50 miles) from Toronto's Pearson International airport. Just over an hour by car or airport limousine (Airways Transit), or with other means of ground transportation.

TRANSPORTATION

Cars may be rented at the Toronto's Pearson International airport. For airport limousine service, consult limousine desk at the airport arrival level. Ground transport is also available with AIRWAYS TRANSIT (tel. 519-886 2121) who are located at the Ground Transportation Desk at the airport. The cost of ground transportation is approximately Cdn$40.00 and payment is by cash only.

WHEN AND DURATION

The workshop will start Friday June 7 at 8:00 p.m. The next day there will be lectures starting at 8:00 a.m. until 6:15 p.m. On Saturday June 8 at 7:30 p.m., there will be a banquet. On Sunday June 9, lectures will start at 8:00 a.m. and proceed to 12:40 p.m. There will be ample time to catch flights out of Toronto the same day.

ACCOMMODATION

Rooms have been reserved at the

UNIVERSITY OF WATERLOO
CONFERENCE CENTRE, VILLAGE 2
WATERLOO, ONTARIO N25 4C1
Tel. (519) 884 5400
Fax (519) 746 7599

Rates single room Cdn. $36.41 per night
twin room Cdn. $30.34 per night per person
(includes bed, breakfast, and taxes)

A number of rooms have also been reserved at the

VALHALLA INN
King and Benton Streets, Kitchener
Ontario N2G 3W9
Tel. (519) 744-4141
Fax (519) 578-6889

Rates single/double Cdn. $80.00 per night
Location: 10 mins by taxi from the University

INFORMATION TO PARTICIPANTS

The individual speakers are expected to provide an original copy of their slides or transparencies used in the talk by May 15, 1991. These will be copied and distributed by the organising committee to the rest of the participants. If there is interest it may later on be published as a monograph.

TECHNICAL PROGRAM

Friday, 7 June 1991
8.00 - 9.00 pm: Registration. Room DC 1301

Saturday, 8 June 1991
7.45 - 8.00 am: Registration. Room DC 1301

All presentations will be held in DC 1302 which is next to DC 1301.

Chairman: *Savvas Chamberlain*

8.00 a.m. Introduction: *Savvas Chamberlain*

8.10 a.m. Fabrication Techniques Of CCD's for Performance and Yield
Sat. 1

Richard A. Bredthauer
Loral Fairchild
Newport Beach, CA 92658-8900

Abstract
A detailed overview of CCD processing techniques will be per- formed will be performed. Various tradeoffs will be explored to demonstrate optimum process parameters for maximizing particular system performance requirements of scientific imaging CCD's. Topics discussed will include:

- Tradeoffs in double and triple level polysilicon.
- Processing necessary for multi-pinned phase CCD's, virtual phase, open pinned phase and notched CCD's.
- Device simulation procedures utilizing Stanford Supreme3, Pisces and Supreme4.
- Integration of CMOS and CCD process technologies.
- Lightly doped drain implementation for low noise performance.
- Future CCD materials technologies such as Germanium and Diamond.

9.05 a.m. III-V CCD'S
Sat. 2

Eric R. Fossum
JET PROPULSION Laboratory
Pasadena, CA

Abstract
III-V CCD's have been demonstrated to operate at frequencies up to 4 GHz and are anticipated to operate even faster. This talk will present the basic principles of both MESFET-type and two dimensional electron gas (2DEG) type CCD's, including both capacitive-gate and resistive gate configurations. This talk will be illustrated with examples of actual device structures and operating characteristics. Topics will include:

- MESFET type CCD
- Gate structure. Capacitive gate. Resistive gate.
- Input and Output
- Experimental Results
- Applications
- Future directions
- 2DEG CCD's Structure. Simple equations. Charge transfer. Choice of gate structure. Input and output
- Results. Future directions.

9.55 a.m. Future Development for Thinned Back-illuminated CCD Imagers
Sat. 3

Chin-Ming Huang
Lincoln Laboratory
Massachusetts Institute of Technology
Lexington, MA, 02173-9108

Abstract
Will present different fabrication approaches and quantum efficiency models for thinned back-illuminated CCD imagers. Based on Experimental and theoretical results, future development efforts for these CCD imagers will then be discussed.

- Comparisons of front and back illuminated CCDs
- Comparison of measured Q.E. of front and back-illuminated.

- Lincoln-lab's wafer scale back-illuminated CCDs and package device. Yield and throughput of fabrication.
- Fabrication techniques Conversion of a CCD from front-illumination to back illumination
- Bubble free wafer-scale mounting and choice of epoxy for wire bond reliability.
- Wafer scale thinning process.
- Selective thinning chemistry and stain removals.
- Uniformity and surface morphology of thinned wafers.
- Discussion of mounting wafer in glass and silicon substrate.
- Back surface passivation and analysis
- Critical issues in back-surface passivation
- Overview of approaches for back surface passivation. p+doped surface, biased-gate, silicide and wavelength conversion coating.

10.50 a.m. BREAK

Chairman: *Marvin White*

11.05 a.m. *Sat. 4*
Low Noise Charge Sensing at the Output of a CCD

K. Kandiah and F.B. Whiting
Rutherford Appleton Laboratory Chilton
Oxon OX11 0QX, United Kingdom.

Abstract
The state of the art in low noise MOS-CCDs is reviewed. The performance of an ideal depletion mode MOSFET in a MOS-CCD is analysed from the physical mechanisms. Causes of excess noise (1/f) in current devices are described and possible solutions are proposed. The performance of a PN CCD is analysed.

- State of the art of low noise CCD's
- Noise Model of ideal depletion mode MOSFET
- The Excess 1/f noise in MOS-CCD's
- Charge detecting field effect transistors (CDFET's) for 1e noise floor.

12.00 *Sat . 5*
Models of the back surface of thinned CCD's

Morley M. Blouke
TeKtronix Inc.
Beaverton, OR 97077

This talk will review the state of the back surface of the CCD. The discussion will center on the physical and mathematical models of the back surface and then outline various techniques that are used to enhance the short wavelength response of back- illuminated devices. Finally comparison with the theoretical results will be made.

Outline:
- Introduction
- Theory current models
- Enhancement techniques
- Comparison with experiment
- Summary

12.30 p.m. LUNCH

1.30 p.m. *Sat. 6*
CCD Device Development for use in High-speed sampled analog signal processing

J. D. Strombosky, R.H. Whiting,
C.W. Christensen, D. McClure, R.L. Wixted
Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, MA 02173-0073

Abstract
In this talk high speed buffer memory, matched filtering and discrete Fourier transform CCD devices will be presented. Critical design issues for each device as well as the infamous high-speed CCD clock driver problem will be discussed.

- Illustrative applications of sampled analog signal processing
- CCD device architecture and critical design issues
  High Speed Buffer memory
  Matched Filter Discrete Fourier Transform

- CMOS/CCD Technology Integration
  Motivation and objectives
  High speed CCD clock drivers
  I/O Calibration and peripheral circuitries
- Simulated and experimental Results

2.25 p.m. *Sat. 7*

Semiconductor Device Simulation for CCDs Using Drift-Diffusion and Hydrodynamic Formulations

John R.F. McMacken, Savvas G. Chamberlain
Electrical and Computer Engineering Dept.
University of Waterloo
Waterloo, Ont. Canada N2L 3G1.

Abstract
We review modern models for the numerical simulation of semiconductor devices. The limits of the traditional drift-diffusion formulation are discussed and the hydrodynamic model is presented. This is linked to the various mobility and recombination expressions that are required. Typical discretization and solution techniques are described and numerical results from a variety of device structures are presented.

Outline:
- Introduction
- The need for numerical simulation. What is involved (modeling, discretization, solution)
- The drift-diffusion model
  Assumptions, variable sets, transient vs. steady state, one-carrier vs. two-carrier
  1-D, 2-D, 3-D formulations
- Limits of drift-diffusion: The hydrodynamic formulation
  Small geometry and high electric fields, alternative models.
- Physical properties
  Mobility, lattice vibrations, impurities, surface scattering, velocity saturation
  Recombination. Schockley-Read-Hall, Auger, impact ionization.
- Discretization. Assumptions, orthogonal grids, triangular grids, refinement.
- Solution methods. Coupled vs. uncoupled, linear systems, direct and indirect approaches.
- An example - The CHORD simulator
  Device definition, grid generation and refinement, memory and CPU requirements.
- Typical results
  1-D, 2-D, 3-D simulations

3.15 p.m. **BREAK**

Chairman: *Eric Fossum*

3.30 p.m. *Sat. 8*

An Overview of the Schottky-Barrier Imager Technology

Walter F. Kosonocky
New Jersey Institute of Technology
Newark, NJ 07102

Abstract
This presentation will review the progress in the development of infrared image sensors with Schottky-barrier detectors (SBD's). It will include the summary of the reported detector and imager performance characteristics and other outstanding issues.

Outline:
- Modeling and characteristics of SBD's
- Fabrication technology
- Design choices and trade-offs for starting SBD arrays
- Review of reported SBD imagers and comparison of their characteristics

4.25 p.m. *Sat. 9*

Design and performance considerations for CCD's in acoustooptical channelizers

Stephen Strunk, William D. Washkurak
DALSA INC.
Waterloo, Ont. Canada N2V 2E9

Abstract
CCD's designed for Acousto-Optical Channelizers face some of the most demanding performance requirements. Typical specifications include video rates (per output) of 20 MHz

and a spurious- signal-limited power dynamic range of 60 dB. This workshop session addresses many of the design issues associated with the such high performance CCD's. Additionally, concepts and issues for randomly addressable imaging arrays for such applications are discussed. The contents of the talk include:

- System Requirements
- Device Architectures Linear arrays
  Random Access Linear Area Arrays
- Photoelement Architectures
- Output structures and noise considerations
- Other Performance Issues
- On-chip signal Processing

5.20 p.m. Design of Solid-State Imaging Arrays
Sat. 10

Marvin H. White
Lehigh University
Bethlehem, PA 18015

Abstract
The design of solid-state imaging arrays is presented by optimizing a figure-of-merit (FM)=(S/N)×MTF from the systems point of view. The concept of a noise equivalent signal (NES) is introduced as well as responsitivity to describe the sensitivity of the photosensor to a broadband irradiance over a spectral band. The distinction between radiometric and photometric units is emphasized in this treatment. The talk will include:

- S/N ratio is formulated at the collection diode of the imager with a discussion of various noise sources (i.e. thermal, shot, 1/f, photon, amplifier, clock jitter, power supply, A/D quantization, etc.).
- The MTF is formulated in terms of the sensor geometry, diffusion of generated carriers, transfer inefficiency and signal processing bandwidth, and system lens properties.
- Special consideration is given to the reduction of noise through the use of correlated double sampling (CDS) which effectively removes the Nyquist noise at the collection diode due to the reset switch and suppresses the 1/f noise of the on-chip amplifier.
- NES may be minimized with an optimum design of the on-chip amplifier. Linear, area, and TDI arrays are considered in the design of imaging arrays.

6.15 p.m. RECEPTION (Complimentary Bar)
Room DC 1301

7.30 p.m. BANQUET
Flamingo Room (South Campus Hall)

Sunday, June 9

Chairman: Ying L. Yao, Tom H. Lee

8.00 a.m. Announcements: Savvas Chamberlain

8.10 a.m. A Review of Photo Detector Elements for Interline CCD
Sun. 1

T.H. Lee, B. C. Burkey
Eastman Kodak Company
Rochester, NY 14650-2008 USA

Abstract
The photodetector element is one of the key components in the interline CCD imagers. in addition to detect photo signals, it also used for antiblooming control, electronic shutter and crosstalk reduction. it presents interesting device physics problems and poses exciting design challenge. We will review the evolution of photodetectors used for interline CCD's and discuss the associated problems and issues in designing and evaluation of these components.

Outline:
- Photocapacitor
- np Junction photodiode
- Photoconductor layers
- p+np Multiple Junction Photodiode
- Problems and issues of Photo Detector Elements
  Photo Response, Lag, Crosstalk and Smear, Blooming control, Electronic Shutter
  Non-linearity, Dark current and Noise.
- Future Directions.

9.05 p.m. *Sun. 2*

Time Delay and Integration (TDI) Charge Coupled Device (CCD): Device design and applications

Hon-Sum Wong, Ying L. Yao,
Eugene S. Schlig
IBM Thomas J. Watson Research Center
Yorktown Heights
N.Y 10598, USA.

Abstract
Device design issues of the TDI-CCD will be discussed in detail. Emphasis will be given to considerations such as the parallel array, serial-to-parallel interface, serial register, motion synchronization, clocking MTF, number of integrating stages, noise dynamic range and sensitivity. Including other properties which have an effect on the total system performance.

Outline:

- Historical perspective
- TDI mode of operation
  Principles, examples of implementation, advantages and disadvantages.
- Device design (monolithic silicon TDI - CCD)
  Parallel array, parallel to serial interface, serial readout register, motion synchronization, MTF degradation, effective resolution, clocking, discrete charge motion and MTF.
  Number of TDI stages, sensitivity, exposure control, noise, dynamic range, pixel size, spectral response.
- Comparison with linear photodiode arrays.
  Quantum efficiency, sensitivity, horizontal pitch, resolution, device size, yield, uniformity, ease of operation.
- Design case studies of a family of TDI - CCD
  Target applications, device design trade-off, examples of applications, flat-bed scanner, bank check scanner, high quality art work scanner.
- Future trends and major development issues, high resolution TDI-CCD, large TDI-CCD arrays, one-pass color scanning, others.
- Conclusions

10.00 a.m. *Sun. 3*

An MTF measurement technique for small Pixel Imagers

Mike Marchywka, Dennis G. Socker*
Naval Research Laboratory
Washington DC 20375-5000
* Interferometrics Inc. USA.

Abstract
We have devised an interferometric MTF measurement technique which avoids the complications of precision optics encountered with traditional techniques. The technique has been tried on a KAF-1400 imager and found to give results in close agreement with a charge diffusion model. The outline is:

- Introduction - problems with traditional techniques
- Theory of our technique
- Apparatus sketch, experimental results.
- Fourier transforms of interferograms
- MTF results for a KAF-1400 at 6328A
- Discussion and Summary

10.25 a.m. BREAK

Chairman: *William Washkurak*

10.40 a.m. *Sun. 4*

Modulation Transfer Function (MTF) of CCD Imagers: Utility, Models, and Measurement Methods

Terrence S. Lomheim
The Aerospace Corporation
Los Angeles, CA 90009-2957

Abstract
This talk will address the utility of MTF as an imaging system figure-of-merit. It will deal with MTF models for CCD imagers, characterization measurement techniques including MTF measurement methods for TDI CCD imagers. Finally measurement issues associated with small pixel CCD's will be addressed. Topics to be covered include:

- Utility of the MTF as an imaging system figure-of-merit
- Basics Relationship between the point spread, line spread, and edge spread functions and the MTF. Definitions of contrast ratio, contrast transfer function and their relationship to MTF Effects of spatial sampling and aliasing.
- MTF Models for CCD Imagers
- MTF Measurement /Characterization Methods
- Input Imagers and Patterns
- Measurement of the MTF of Scanned TDI CCD's
- Global MTF characterization of CCD arrays
- Conclusions
  Challenge for future small pixel/large area CCD's: measurement and modeling.
  Perspective of the MTF an imaging CCD figure-of-merit.

11.35 a.m. CCD Image Sensors for HDTV
Sun. 5

Nobu Teranishi
NEC Corporation
1120, Shimokuzawa, Sagamihara
Kanagawa 229, Japan

12.30 p.m. Closing Remarks: Savvas Chamberlain

12.40 p.m. CCD WORKSHOP ENDS