Design and development of a silicon segmented detector for 2D dose measurements in radiotherapy

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Abstract. Modern radiotherapy treatment techniques, such as Intensity Modulated Radiation Therapy (IMRT) and protontherapy, require detectors with specific features, usually not available in conventional dosimeters. IMRT dose measurements, for instance, must face non-uniform beam fluences as well as a time varying dose rate. Two-dimensional detectors present a great interest for dosimetry in beams with steep dose gradients, but they must satisfy a number of requirements and, in particular, they must exhibit high spatial resolution. With the aim of developing a dosimetric system adequate for 2D pre-treatment dose verifications, we designed a modular dosimetric system based on a monolithic silicon segmented module. State and results of this work in progress are described in this article. The first 441 pixels, 6.29×6.29 cm^2 silicon module has been obtained by ion implantation on a 50 μm thick p-type epitaxial layer. This sensor has been connected to a discrete readout electronics performing current integration, and has been tested with satisfactory results. In the final configuration nine silicon modules will be assembled together to cover an area close to 20×20 cm^2 with 3969 channels. In this case the readout electronics will be based on an ASIC capable to read 64 channels by performing current-to-frequency conversion.

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1. Introduction

Radiation therapy uses high energy photons (X or γ rays) or charged particles (electron or proton beams) to treat malignant disease. In particular, conformal radiotherapy techniques shape the irradiated volume to the target, while keeping the dose to surrounding tissues below their tolerance value. Intensity Modulated Radiation Therapy (IMRT) is currently one of the most advanced form of conformal radiotherapy. It allows one to deliver dose selectively to a 3D target by: i) irradiating the patient through many beams having different directions and entry points and ii) by modulating in space the fluence of each radiation field. Fluence modulation can be obtained by a linear accelerator (LINAC) equipped with a multileaf collimator (MLC). MLCs incorporate many pairs of narrow, closely abutting tungsten leaves. Each leaf is individually motorized and computer controlled. As a result, IMRT dose distributions are characterized by complex dose spatial gradients and time-dependent fluence delivery [1].

Two-dimensional (2D) detectors present a great interest for pre-treatment dose verification in conformal radiotherapy. Anyway, in order to reach a level of accuracy which can be considered acceptable, 2D detectors must satisfy a number of requirements. In particular, they must have high spatial resolution in order to reproduce the steep dose gradients inside the treatment field and in the penumbra region. Moreover, 2D detectors should be able to withstand the large cumulative doses associated with the routine application and they should also provide a linear response in a large range of doses.

Film dosimetry is a well established method to verify 2D dose distributions in phantoms [2-4] because spatial resolution is limited only by the reading system. On the other hand, the dynamic range is rather small; dose response is non-linear; a labor-intensive readout is needed. On the market, devices are also available constituted by an array of sensors. In this case, the response is immediately available in digital form. The spatial resolution and granularities (i.e. pixel pitch) are however worse than with films. As an example, some commercial products are the PTW 2D array (729 ionization chambers, covering an area of 27×27 cm^2, ~10 mm pitch); Sun Nuclear MapCHECK (425 Si diodes, 22×22 cm^2 area, 10 mm pitch) [5]; Scanditronix-Wellhofer MATRIXX (1024 cylindrical ionization chambers, 24×24 cm^2 area, 7.5 mm pitch) [6].

We proposed to develop a 2D dosimetric system based on segmented monolithic silicon sensors. Silicon is attractive from many points of view: 1) the relation between crossing photon energy and number of electron/hole pairs produced in the bulk is linear. 2) Sensitivity is quite high (≈3.6 eV/pair); as a consequence it does not limit the active volume, which can be reduced to obtain high spatial resolution. 3) A well developed technology for the production of segmented monolithic planar detectors, widely adopted in high energy physics, is available. 4) Granularity is practically limited only by the increasing number of channels and readout electronics complexity.

2. Specifications

The detector (i.e. the Si sensor connected to readout electronics) should reveal X rays produced by a medical LINAC. These machines accelerate electrons to kinetic energies from 4 to 25 MeV using microwave fields. X rays are produced by bremsstrahlung in the head of the machine. Commercial LINAC typically generate X ray pulses with a duration of few μs and pulse repetition frequency (PRF) in the range ~50-400 Hz. PRF can be varied to change the dose rate in the range ~0.5-4 Gy/min. During the delivery the PRF is constant, but dose rate changes because MLC configuration varies in the time. The leaf movements take place on a time scale of ~1s. The device needs not to resolve the time structure of X ray pulses, but only to measure the dose (i.e. to integrate the dose rate) and, for certain applications, to reveal dose rate variations due to leaf movement. For this reason, the dosimeter will operate in current-integration mode with an integration time variable in the range 0.1-2 s. This is in agreement with the operation mode of the LINAC, where the dose delivery is monitored by ionization chambers, integrating the ionization current on the beam line.

The Si sensor must cover an active area of at least 20×20 cm^2, with a granularity of the order ~1mm. An area so large cannot be covered with a single monolithic sensor, thus it is necessary to assemble many Si modules close to each other. The dark signal should be lesser than 0.1% of signal and this require zero bias operation.

Radiation tolerance is a major concern. Silicon diodes for dosimetry applications suffer of macroscopic radiation damage mostly in terms of sensitivity decrease, dose rate dependence for pulsed beams and increase of dark current (which, in turn, produces an increase of the noise). This problem has been addressed by choosing sensor material and geometry, as discussed in the next section.

3. Sensor

3.1. Choice of sensor material

At null bias operation, the sensitivity of a Si junction is proportional to the minority carrier diffusion length $L=(D\cdot\tau)^{1/2}$, with D diffusion constant. The minority carrier lifetime τ decreases with the dose Φ, due to radiation-induced creation of defects in the lattice: $1/\tau=1/\tau_0+K\Phi$, with τ_0 minority carriers lifetime at zero dose. The decrease in sensitivity is characterized by a fast decay, dominant for doses up to 10 kGy (for 20 MeV electron beams), plus a slower degradation dominant at higher doses [**7**]. The response for a n-type detector depends on the dose per pulse at high dose, whereas the response for a p-type detector is independent of dose per pulse. Thus, commercially available Si diodes are p-type and usually pre-irradiated up to about 10 kGy with 20MeV electrons [8,9]. In this case, $L\approx60$ μm and $\tau\approx3$ μs. Still after this pre-irradiation, the device shows a further decay in sensitivity with the accumulated dose, and Si dosimeters require a frequent recalibration.

Our original approach has been to fix the active volume of the device by defining its planar active area as exactly as possible (by using a guard-ring structure to be grounded during operation) and by limiting the active depth (by implantig the diode on an epitaxial layer) to values shorter than L at the highest operative dose. The effectiveness of this choice has been proved by test of p^+n and n^+p junctions produced on different starting materials (Czochralski, Floating Zone, Epitaxial on Czochralski Si) and with different guard-ring to pad distances d. These devices have been irradiated with γ-rays from ^{60}Co and with 6 MeV electrons from a LINAC up to the accumulated dose of 10 kGy [10]. Epitaxial diodes with w=50 μm thick epitaxial layer and a guard ring very close to the electrode (d=10-20 μm) resulted to be the radiation hardest: the current response to a ^{60}Co beam slightly decreases (3.5 %) up to 1.5 kGy and then stays almost constant up to 10 kGy. In this case the pixel active volume is $\approx w(b+d)^2$, b indicating the lateral size of pad implant. Deviations from this value may be due to doping gradients and electric field fringing.

3.2 441 channels Si module

Several 6.29×6.29 cm^2 Si modules have been obtained starting from 4" p-type MCz wafers. Nine modules can be assembled in a 3×3 array to cover an area close to 20×20 cm^2. Epitaxial layers with 50 μm thickness have been grown by ITME, Warsaw, Poland. The final design of the module is shown in fig.1. Soft-gray areas are n^+ implants (passivated), while dark-gray areas indicate metalizations. The module (a) is composed of a 21×21 pixel matrix, with a total of 441-channels. Four pixels (b_{11}, b_{12}, b_{21}, b_{22}) are put into evidence in the figure. The best compromise between granularity and electronic complexity has been achieved by choosing pixels with 2×2 mm^2 active area and 3 mm pitch. All the wide implants (c) surrounding pixels form the guard-ring. The distance between pixels and guard-ring implants is 20 μm. Thin lines ($d_{1\text{-}21}$, $d_{22\text{-}42}$) running above the two columns of pixels are the over-metal strips (20 μm width) connecting each pixels to the pads, which are aligned along the lower corner of the device (e) to allow an easier bonding to readout electronics. Strip pitch is 95 μm within each column and 140 μm on the average. Manufacturing of the device (Italian patent No. FI2006A000166) has been carried out by ITC-IRST in Trento. Test under probe station gave very good results. The generation current at zero bias, measured by a HP41421B source-monitor unit, is i_0=13±7 pA; its temperature coefficient around 20 °C is $di_0/dT \approx 4$ pA/°C. The coupling capacitance between channels in the same columns due to strip-pixel coupling, measured by a HP 4284A LCR meter, is C_c~2 pF. The total capacitive load of a channel toward ground is ~50 pF.

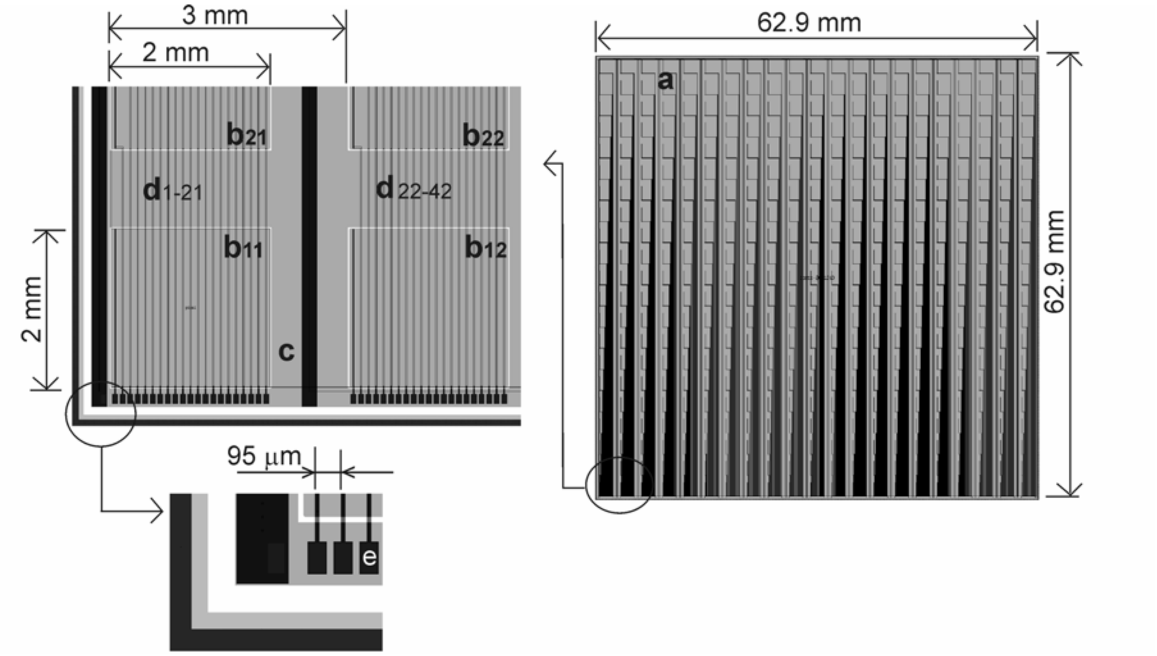

Fig. 1. Geometry of the 441 channels Si module. Enlarged details of the lower left corner are shown on the left.

3. 441 Channels detector

Our first prototype has been obtained by connecting a Si module to a discrete-components readout electronics. System architecture is shown in fig.2. The current from each channel ($I_{0\text{-}440}$) is integrated by a low-bias operational amplifier (LMC6084) through a capacitance C=1.00±5% nF. Circuitry has 512 input channels, but 71 are unused in our application. Integrating capacitances are reset with period T in order to prevent output saturation. Integrator analog outputs are multiplexed by a factor 8. Multiplexed outputs $AI_{0\text{-}63}$, are then digitized by a 12 bit, 64 input channels commercial DAQ (NI6071E). Frame clock (1/T), which fixes integration time, is generated by a voltage controlled oscillator (VCO). Integrators reset and multiplexers selection address S_{0-2} are generated on board according to the controls signals coming from the DAQ. The range of integration times is T=0.1-2 s. All channels are sampled in sequence in a period shorter than 500 μs before reset thus, in the very worst case, the difference in integration time between the first and the last channel to be read is 0.5%.

Noise of bare readout electronics is pretty low: σ=1.2 mV±0.5% of signal, and is determined mainly by operational amplifiers. The dynamic range is limited at low voltage by the output background signal $V_{bk}\cong 20$ mV due to the charge injected by multiplexers toward integrating capacitance. The sensitivity (≅1V/nC) of various channels has been measured by feeding inputs with a constant current and its reproducibility is close to 5%.

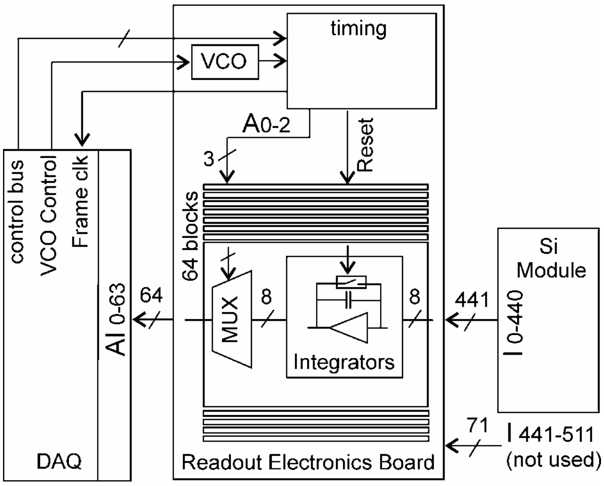

Fig.2. Architecture of 441 channels prototype

The assembled detector is shown in fig.3. One Si Module (a) is mounted on a Printed Circuit Board (PCB, c). In the first prototype, a pitch adapter (b) was used to change the line pitch from 95 μm (pads on Si module) to 250 μm (strips on a standard PCB). Connections between pitch adapter and module were established by wedge-bonding. Bonds are made by an automatic bonder machine Delvotec 6400 using 25um Al wire (1%Si). In a subsequent prototype, the module pads have been bonded directly to a high density PCB (140 μm strip pitch); this solution is less expensive and improves signal-to-noise ratio SNR. Electronics is accommodated on a number of small boards (e), each of which is dedicated to integration and multiplexing of 16 channels. All these small boards are then connected by vertical mounting to a mother board (g), in order to save space and shorten connections. Outputs of multiplexers are routed by drivers to the DAQ by a 100 ways cable (f). The upper side of the box is closed by a black polystyrene sheet (g) to shield light and some PMMA layers (h) to reproduce experimental conditions recommended by radiotherapy protocols. A lead shield (i) upon aluminum closure is used to prevent photons to damage integrated circuits.

The dosimetric characterization of this detector is reported and discussed in ref.[11]. Typical performances are (using T=0.2 s): sensitity s=1.25 nC/cGy, dark signal q_0=19 pC, noise level σ=20 pC; signal to noise ratio SNR=119 with a dose rate R=177 cGy/min.

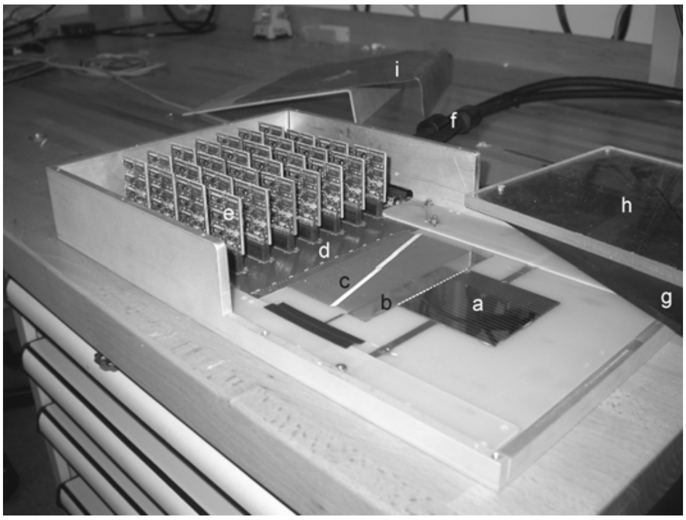

Fig.3. Photograph of the 441 channels detector prototype.

4. Large scale detector

4.1 Choice of ASICS

In order to construct a compact readout electronics, with short connections, high reliability and low power consumption, we looked for an integrated device capable to replace a large part of the electronics based on discrete operational amplifiers. A promising candidate has been found in the Tera chip designed by Turin INFN division and produced by Wellhofer-Scanditronix. It performs the readout of 64 input analog channels and the digital conversion from integrated charge to counts (charge quanta) with good noise performances, sensitivity and radiation hardness [12]. We have tested a sample TERA chip (version 03) with an input current in the range i=0.1 pA-50 nA by using a Keithley 6430 source-meter unit. We set a sensitivity of about 41.0 Hz/pA and measured a SNR>100 as long as i>10 pA. In this current range, the deviation from linearity is better than 0.6%

and the reproducibility is better than 1%. These results are in agreement with the characterization carried out by TERA design team [12].

4.2 Overall design

The overall design is shown in figure 4, on the left side. A large active area of about 19×19 cm^2 is covered by 3969 channels by placing nine 6.29×6.29 cm^2 silicon modules (a_1-a_9) side by side. Each module is connected by bonds to a high density PCB (b_1-b_9) carrying readout electronics. The central module (a_5) cannot be placed beside a PCB, and its output must be routed by conductive strips printed on a Kapton sheet (f). The digital outputs of each PCB are connected to a common bus (c) on the "mother board" (g). Data acquisition and electronics control is performed a by a FPGA (e) which communicate to a personal compute (PC). The PCB structure (top layer) is shown in detail on the right side of the figure. The 441 outputs of each silicon module are routed through 140 mm pitch strips from detector side to 7 Tera (version 06) dies (d_{1-7}, about 5.4×4.5 mm^2 size). Dies are mounted 3 cm away from PCB edge on detector side to reduce irradiation by scattered photons.

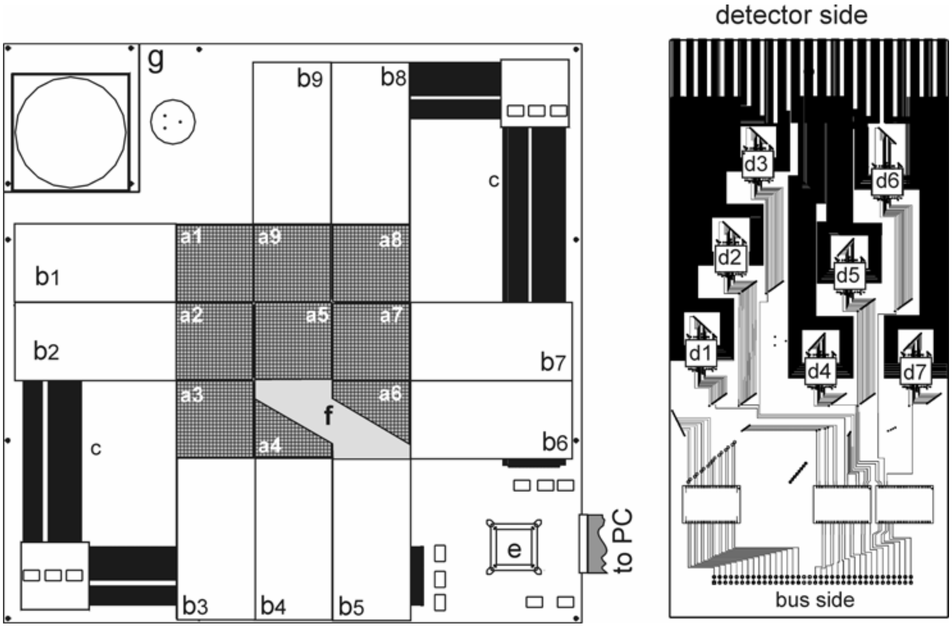

Fig.4. Overview of the large scale detector (left) and details of readout electronics (right) .

5. Conclusions

With the aim of developing a dosimetric system adequate for 2D pre-treatment dose verifications in radiotherapy, we designed a modular dosimetric system based on a monolithic silicon segmented module. Results and state of this work in progress are described in this paper. Material and module geometry have been chosen after extensive radiation hardness tests with γ rays from ^{60}Co and 6 MeV electrons. The first 441-pixels 6.29×6.29 cm^2 module has been obtained by ion implantation on a 50 μm thick p-type epitaxial layer. This module has been connected to a discrete readout electronics performing current integration, and has been tested with satisfactory results. In the final configuration 9 silicon modules will be assembled together to cover an area close to 20×20 cm^2 with 3969 channels. In this case, readout electronics must be based on a suitable ASIC. The chip TERA (produced by Scanditronix-Wellhofer) has been tested and selected to this purpose; it is capable to readout 64 channels by performing current-to-frequency conversion. The printed circuit boards needed to construct this advanced prototype have been designed and are presently being manufactured. The mounting of first Si module with TERA-based readout electronics is scheduled for the end of 2006, debug for may 2007 and beam test in September 2007. The full system composed of 9 modules should be assembled and tested during 2008.

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