EVALUATION OF SILICON DIODES AS IN-SITU CRYOGENIC FIELD EMISSION DETECTORS FOR SRF CAVITY DEVELOPMENT. *

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Abstract

We performed in-situ cryogenic testing of four silicon diodes as possible candidates for field emission (FE) monitors of superconducting radio frequency (SRF) cavities during qualification testing and in accelerator cryo-modules. We evaluated diodes from 2 companies - from Hamamatsu corporation model S1223-01; and from OSI Optoelectronics models OSD35-LR-A, XUV-50C, and FIL-UV20. The measurements were done by placing the diodes in superfluid liquid helium near the top of a field emitting 9-cell cavity during its vertical test. For each diode, we will discuss their viability as a 2K cryogenic detector for FE mapping of SRF cavities and the directionality of S1223-01 in such environments. We will also present calibration curves between the diodes and JLab's standard radiation detector placed above the dewar's top plate.

INTRODUCTION

Modern superconducting radio frequency (SRF) cavities for use in particle accelerators are often limited by field emission and/or dark currents. Not only does the emission limit the cavities performance, it can activate parts [1], permanently damage the cavities [2], and disrupt the beam in the accelerator. [3] In many cases, the cause and location of the field emission is not known, and therefore an effective field emission reduction strategy is not available. A full 3-D mapping system coupled with a reliable theoretical approach is needed before a systematic study of FE reduction can be undertaken. Multiple 3-D x-ray mapping system have been developed in the past for this purpose using mostly Hamamatsu diodes, for 700 MHz 5 cell (Hamamatsu S1722-02) [4] for 1.3 GHz ILC (Hamamatsu S5821-02) [5], single and 9 cell ERL cavities (Hamamatsu S5821-02) [6–8], and for x-band cavities (Siemens BPX66) [9]. In addition to cryogenic field emission monitoring systems, silicon photo diodes are also being used as electron energy detectors at 10K and in high magnetic fields (Hamamatsu S3590-06). [10]

In an effort to determine which diode would be best for Jefferson Laboratory's (JLab) new field emission mapping system we evaluated diodes from 2 companies - from Hamamatsu corporation model S1223-01; and from OSI Optoelectronics models OSD35-LR-A, XUV-50C, and FIL-UV20. We were able to determine the perennial Hamamatsu S1223-01 is still the best silicon diode in terms of cost per performance. In addition, the more expensive direct detect x-ray silicon diodes do not give any real world performance advantage even though they are thicker and/or fully depleted when using a 15V reverse bias charge sensitive amplifier. The one inversion layer diode tested did not perform nearly as well as standard diffusion PIN diodes in cryogenic x-ray detection. The dose scaling for all diffusion diodes relative to JLab's standard ion probe is $1mR/hr \approx 1mV$ ($10\mu Sv/hr \approx 1mV$).

SILICON PIN DIODES

As part of the development of a field emission mapping system, five different diodes from two different companies were evaluated. A table contain the compiled data for all 5 diodes is show in Table 1. From Hamamatsu corporation models S1223-01 and S5821-02 [11] and from OSI Optoelectronics company models OSD35-LR-A [12], XUV-50C [13], and FIL-UV20. [14] Both Hamamatsu diodes have been used in the past at KEK(S1223-01 and S5821-02) [15] and Jefferson lab (S1223-01) [16]. The S5821-02 never gave a clean signal above 50mV and was abandoned early on in experimentation, so no data will be reported on this diode. The OSI diodes have some addition features that the Hamamatsu diodes do not have. The FIL-UV20 is the only inversion layer photo-diode; it contain a plastic package and quartz windows. [14] The OSD35-LR-A is a fully depleted PIN diode in a ceramic package with no window, only an epoxy resin sealing layer. The XUV-50C is a soft x-ray direct detect PIN diode in a ceramic package with removable quartz window (used during test). [13]

TEST SETUP

Each diode was placed approximately 6 inches above the end cap of ILC R&D cavity TB9RI-023 (RI23) inside the 2K cryostat. RI23 is a field emitting cavity which is

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Table 1: Diode Comparison Data

Model	Active area (mm^2)	Capacitance	Cost ($)	Standard use	Package type	Company
S5821-02	1.4	3pF	6	high speed data	metal	Hamamatsu
S1223-01	13	20pF	12	high speed data	metal	Hamamatsu
FIL-UV20[a]	20	1000pF	27	UV light	plastic	OSI
OSD35-LR-A	34.2	1300pF	55	x-ray/scintillators	ceramic	OSI
XUV-50C	50	2-3nF	360	x-ray to 17.6KeV	ceramic	OSI

[a] only inversion layer diode

field emission induced quench limited to 18MV/m. Each diode was connected to a charge sensitive voltage amplifier (reverse bias mode) located outside the dewar, above the top plate. All diodes were tested in the same configuration with a reverse bias voltage of 15V, below the damage voltage for all diodes even though the x-ray diodes could handle a higher bias. The amplified signals were then fed into a NI USB-6356x series DAQ card operated in Labview. The NI USB-6356x was chosen because of the channel to channel isolation and fast sampling time (up to $1.25MS/s/ch$). The system was set to take continual data sampling at $100KS/s$. The radiation dose measurements were take above the top plate outside the cryostat about 6 feet from the cavity top by a Canberra AM-IP100 Area Monitor. The transmitted power (Eacc), diode voltage and radiation dose were taken simultaneously on individually isolated channels.

RESULTS

In order to compare the diode response, we fit the diode voltage vs. cavity accelerating gradient data to a generalized Fowler-Nordheim equation. [17] A example of the fitting is show in Figure 1 (Top). In general, the low voltage measurement below 10mV were hard to fit as the signal to noise is not constant as it is above 10mV. The compiled data from all 4 diodes is shown on Figure 1 (Bottom). One can see that all three diffusion layer diodes (XUV-50C, OSD-35-RL, S1223-01) performed essentially identically with a radiation turn on around 11MV/m and a 600mV signal at 17MV/m. There is a small systematic shift in turn on voltage with activation area with the largest XUV-50 showing a signal at the smallest field. The only inversion layer diode (FIL-UV20) is about 10 times less sensitive than all the diffusion layer diodes.

In order to establish a reasonable scaling factor between the output voltage of a diode and the approximate dose in milliRoentgen per hour of (mR/hr) usually published from ion probe data, we present the diode voltage scaled to JLab ion probe Canberra AM-IP100 (Figure 2). In our case, it appears the two outputs have the same shape; to match the output of the Ion probe the voltage on the diode need to be scales with $1mV \approx 1mR/hr$ (i.e. $1mV \approx 10\mu Sv/hr$). There are two items to note in the measurement; one, the ion probe appears to have 3 decades more sensitivity than the diodes, and two, the scaling seems rather good even though the diodes are close to the cavity and ion probe is 6 feet away and 2 feet off axis above the top plate.

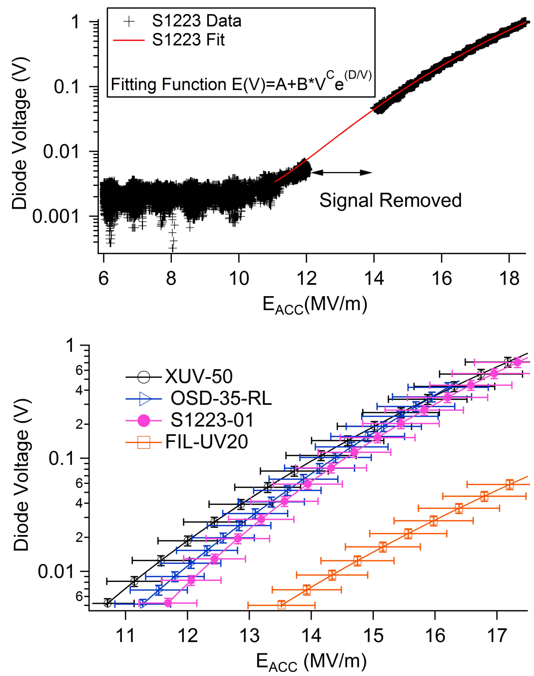

Figure 1: (Top) Example of raw data and fitting function extraction for diode comparison. Data fit with $E(V) = A + B * V^C e^{\left(\frac{D}{V}\right)}$, where A,B,C,D are allowed to float. The signal from 12-14 MV/m were taken our because of a quench during the slow power rise. (Bottom) Comparison of all 4 diode voltage extracted from the fitting procedure above; Black open circles - XUV-50C, blue open triangle - OSD-35-RL, pink closed circles - S1223-01, and orange open squares - FIL-UV20.

One other item that needs to be addressed in building an effective field emission mapping system is the angular dependence of the diodes. On would expect the angular dependence to be somewhere between a cos function and a constant with angle. The cos would come from the surface area perpendicular to the radiation and the constant if the radiation goes through. Our data (Figure 3) does seem to show some angular dependence where the highest voltage is facing the cavity and the smallest is when the

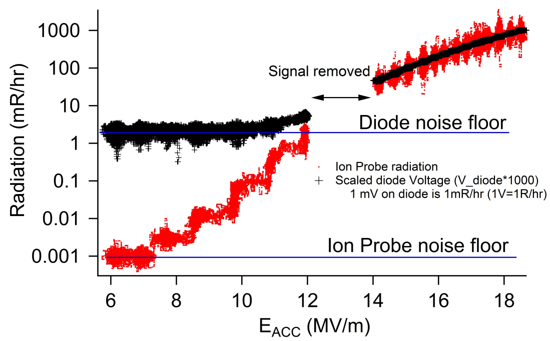

Figure 2: Ion probe dose vs. cavity accelerating gradient in black and scales diode voltage (S1223-01) vs. cavity accelerating gradient in red. The diode voltage matches the radiation dose at where $1mV \approx 1mR/hr$ (i.e. $1mV \approx 10\mu Sv/hr$). The signal from 12-14 MV/m were taken our because of an error in the ion probe voltage during a quench. The blue lines are the noise floor for each system.

diode is perpendicular to the cavity, yet, there is also a large non zero floor. It is unclear where the angular dependence comes from, because we know the x-ray have a high enough energy to pass though the diode. The diodes could also have the same angular dependence as light, but the non-zero floor would come from scattered secondaries. Were were only able to test S1223-01 diodes for angular dependence while the other good diodes (OSD-35-RL and XUV-50) were not tested because we only had one of each. The angular dependence of FIL-UV20 and S5821-02 were not taken because of their small/non signals.

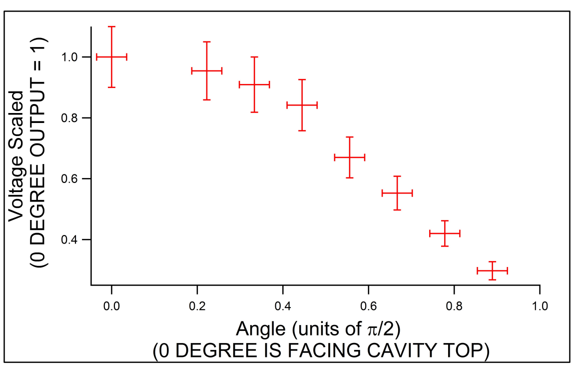

Figure 3: Angular dependence of S1223-01 diodes.

There are a couple of issues to note during our tests. Unlike KEK, we were never able to get a signal from a set of Hamamatsu S5821-02, but initial results were from our older amplifier design and these diodes were abandoned early on. Second, all diodes survived repeated cool downs except the OSD35-LR-A in which one diode failed during the first cold test. Finally, for the S1223-01 and FIL-UV20 diodes we had a set of 8 diodes each, the deviation between each set of diodes was less than 5% - which is smaller than the noise in our amplifiers and within the error of placement above the cavity. The reliability between diodes presumably come from the fact the thickness of each is well regulated by the manufature with modern deposition techniques.

CONCLUSIONS

We have presented a cryogenic test of 4 silicon PIN diodes as field emission detectors for SRF cavity diagnostics. We found the perennial favorite Hamamatsu S1223-01 performed the best in terms of cost and signal to active area. The one inversion layer diode was 10 times less efficient than the diffusion layer diodes. Finally, the voltage on the diffusion diode scales to ion probe dose rate with a conversion of $1mR/hr \approx 1mV$.

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