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MASTER

PRODUCTION AND USE OF HIGH-GRADE SILICON-DIODE TEMPERATURE SENSORS*

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INTRODUCTION

With today's tight budgets and increasing costs, helium refrigeration system engineers must design for increased cycle efficiency and shave the refrigerators excess capacity to reduce capital costs and operating expenses. For a project such as ISABELLE this task is noteworthy since the load is not one easily calculable dewar but 1100 magnets supplied by long transfer lines, interconnecting links and multitudes of lead pots. Realizing the consequences, ISA's cryogenic group has been measuring heat loads of magnets and associated equipment and has confidence in their estimates.

FINDING THE OPTIMAL DEVICE

Since temperature measurement is a kind of common denominator in instrumenting cryogenic systems, work was started in the mid seventies by Brookhaven's 80" Bubble Chamber Group to find a sensor that encompasses all the features of an "optimal" device. My definition of "optimal" device is one which:

- a) Covers the range from above room to below helium temperature
- b) has high output (dV/dt)
- c) is completely interchangeable (matched characteristics)

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- d) has two wire configuration
- e) has stability at helium temperature $> |0.05K|$
- f) is unaffected by magnetic fields
- g) is readily available and inexpensive

Finding an "optimal" sensor is admittedly an impossible task since there is no known single thermometer with these characteristics. However, if one or two requirements are waived the silicon diode comes very close to optimal.

Early work concentrated on finding an easy method to make the sensors interchangeable and to enhance their stability. Work barely began when it was realized that with today's "smart" electrical circuits, electronics should shoulder the burden of interchangeability and not the sensor. The result of this decision is described in an internal technical note entitled, "A Very High Accuracy Cryogenic Digital Thermometer."

DIODE STABILITY

Work then focused on the problem of diode stability. Instability can best be demonstrated by referring to diode junction voltage drop data derived from a series of twenty dip cycles carried out on commercially calibrated silicon diode temperature sensors. Voltage drop variations of fourteen sensors ranged from $+13M.V.$ to $-3M.V.$, $1\sigma = 4.5M.V.$, an equivalent temperature error of $\sqrt{0.09K}$. Their absolute error was worrisome for high accuracy work but far worse were the sensors continual walk throughout thermal cycling.

Groups of commercial signal diodes and transistors were checked for stability by similar repeated dip tests. A total variation of $2M.V.$ junction voltage drop was considered acceptable including all variations from the first dip through the twentieth corresponding to a ΔV_j of $0.05K$ equivalent. The search was enlightening for it was found that:

- a) Many commercial semiconducting devices will function as temperature sensors.
- b) Similar type devices supplied by different manufacturers exhibited different characteristics at low temperatures.
- c) Sensor yield varied from batch to batch when supplied by a single manufacturer.
- d) ΔV_j from the first dip to the last appeared as either a positive or negative function with successive dip data oscillating around the general trend line.

One of better devices tested was the Motorola 2N3906 transistor. A standard stock part at Brookhaven, it comes housed in a TO-92 plastic case at a cost of eleven cents each in thousand quantities. A typical collector-base voltage-temperature characteristic is shown in Fig. 1. The first derivative of V_j is shown in Fig. 2. The yield of sensor grade diodes after seasoning runs between 15 and 40% for the Motorola 2N3906 where as 2N3906 transistors from other manufacturers have yields of less than 10%.

In order to investigate long term stability twenty three previously seasoned and selected sensors were shelved for a period of months and cycled through a second series of twenty dip tests. A factor of two improvement in stability was obtained as a result of the lengthened seasoning process.

Results of the seasoning tests demonstrated that fully documented, stable silicon diodes can be selected but only after a considerable expenditure of time and effort. To make the task less labor intensive a computer based data acquisition system was designed and installed. The system enables an operator to season 30 devices at a time while checking liquid bath temperature and electronics calibration. Dip cycle times were shortened by rapidly warming the diodes to 50°C in hot water as opposed to letting them drift up in the air. The harsher treatment reduced the yield a few percent but it is thought to be beneficial since high thermal stresses tend to be effective in weeding out marginal devices.

CALIBRATION CRYOSTAT

A calibration cryostat was constructed, shown in Fig. 3 to complete the system. It consists of an evacuated pot suspended in a liquid helium filled dewar. Two copper blocks inside the pot were hung from the top flange thermally series connected to the helium reservoir. The bottom mass holds all reference sensors and provides space for twenty four devices to be calibrated. Superinsulation totally surrounds both blocks to mini-

minimize thermal radiation losses. All sensor wiring is thermally heat sunk to the bottom block, threaded up through connecting copper tubing and heat sunk again at the top block. Wiring then exits the pot via a multipin hermetic connector and is brought out through the top flange of the dewar to electronic apparatus. Complete thermal isolation of the bottom block is accomplished by an electronic control loop designed to heat the upper copper mass to be in thermal equilibrium with the lower block. Sensor temperature is changed by the addition of energy to the bottom block by means of a finely controlled electrical heater.

A typical calibration run of twenty four sensors is carried out over a two day period. Sensors are installed, checked electrically and measuring equipment calibrated. The pot is usually precooled to N_2 temperature overnight, helium filled and sub-cooled to 2.4K the next morning. Energy is then added to the lower block to drive the mass up in discrete temperature steps. At each step sensor data is stored in microprocessor memory and echoed via character printer output. A germanium sensor is used as a reference to 50K and a platinum resistance temperature standard for higher temperatures. All stored data is transferred to the computer data acquisition system which generates a calibration sheet for individual devices (Fig. 4) and produces floppy disc data files for recordkeeping purposes. Each sensor is then removed from the pot and dipped in helium once more as a final check.

A computer program was written to plot point to point slopes for each diode calibrated. It was found that the sensors seem to exhibit three distinct signatures (Fig. 5) through their lower temperature range. Data is being accumulated to determine if there is any statistical correlation between signature and stability or failure.

The cryostat system has been used to calibrate hundreds of various types of sensors and aside from occasional vacuum leaks continues to perform satisfactorily.

INDUSTRIAL EXPERIENCE

Testing and calibration of sensors under laboratory conditions is necessary and enlightening but ones education is not complete until the devices are put to work in an industrial environment. About six hundred sensors of both commercial and inhouse types have been used in ISA projects at Brookhaven.

Accumulated failure rate of all devices in service is less than one percent of total. However, some of the problems associated with cryogenic thermometry can be more subtle than

outright catastrophic failure. An example of a cause of catastrophic failure and more subtle problems are discussed below.

a) Sensors mounted in welded transistor cans have higher failure rates on average, increasing to 10 to 20% of those in service. The problem is caused when a small seal leak permits the volume inside the can to equalize with process conditions. A sudden warmup or even slow rise, depending upon the magnitude of leak, over pressures the case and causes the cap to blow off destroying the sensor.

b) Typically all sensors at ISABELLE are installed in the process stream at some point in the construction phase. Assembly, welding and leak checking then continues to completion. Final check out revealed that groups of well seasoned, stable silicon diodes would sometimes be found to have failed

Fig. 3. Temperature Sensor Calibration Cryostat

DATA FROM SENSOR MODEL J906
SERIAL NUMBER 422
TAKEN FROM BX11A00422.DIG

TEST TEMP	VOLTAGE (MILV)	DV/DI (MV/DEGREE)	FREQ (KHZ)	CALCULATED TEMPERATURE	ERROR	BREAKPOINT FREQUENCY(KHZ)	TERMS AND COEFFICIENTS
2.4	1.728100		38.434	2.400034	0.000034	##### 3.8455998E+01	
2.6	1.723100	-25.73	38.906	2.400916	0.000916	# #	
2.8	1.717800	-27.25	39.171	2.400270	0.000270	# #	
3.0	1.712200	-29.00	39.451	2.399625	-0.001945	# #	
3.4	1.699800	-32.75	40.174	3.398710	-0.001290	# #	
3.8	1.684000	-35.50	40.719	3.802773	0.002773	# #	0 2.4000341E+00
4.2	1.671400	-37.50	41.419	4.200661	0.000661	# #	1 8.3115423E-01
4.6	1.654000	-39.12	42.238	4.599547	-0.000453	# #	2 -1.1627522E-01
5.0	1.640100	-40.79	43.082	4.998335	-0.001645	# #	3 2.3482185E-02
6.0	1.598000	-41.40	45.110	4.000473	0.000473	# #	4 -5.0989343E-03
7.0	1.557300	-41.03	47.188	4.999844	-0.000154	# #	5 2.5311470E-04
8.0	1.514800	-39.00	49.211	5.001744	0.001744	# #	6 -1.2229141E-05
9.0	1.479300	-34.10	51.084	6.994233	-0.003743	# #	7 3.2171644E-07
10.0	1.444400	-32.98	52.817	10.003500	0.003500	# #	8 -3.5508934E-09
11.0	1.413500	-29.83	54.371	10.997510	-0.002490	# #	
12.0	1.386000	-27.15	55.799	12.003123	0.003123	# #	
13.0	1.359200	-24.80	57.083	12.994351	-0.001419	# #	
14.0	1.333300	-23.03	58.277	14.002087	0.002087	# #	
15.0	1.313100	-21.50	59.384	15.000010	0.000010	##### 5.9384002E+01	
16.0	1.292300	-20.15	60.423	15.999864	-0.000114	# #	0 1.50000010E+01
17.0	1.272900	-19.03	61.399	17.000443	0.000443	# #	1 8.4008513E-01
18.0	1.254200	-18.25	62.328	17.999045	-0.000955	# #	2 1.8482237E-01
19.0	1.236300	-17.80	63.222	19.000894	0.000894	# #	3 -1.2944531E-01
20.0	1.218400	-18.00	64.104	19.999851	-0.000149	# #	4 5.4102384E-02
21.0	1.200300	-15.04	65.020	20.999494	-0.000504	# #	5 -1.2522429E-02
22.0	1.180400	-21.28	66.010	22.000528	0.000528	# #	6 1.4171447E-03
23.0	1.157730	-23.08	67.144	22.999741	-0.000259	# #	7 -1.1140044E-04
24.0	1.134310	-18.49	68.316	24.000038	0.000038	# #	8 3.1920840E-06
25.0	1.120340	-9.76	69.014	25.000027	-0.000027	##### 4.9014000E+01	
26.0	1.114910	-4.41	69.285	25.999517	-0.000483	# #	
27.0	1.111350	-3.04	69.454	27.001194	0.001194	# #	0 2.5000027E+01
28.0	1.108830	-2.53	69.589	27.999111	-0.000889	# #	1 2.3232248E+00
29.0	1.104440	-2.27	69.707	28.994387	-0.004613	# #	2 4.9521379E+00
30.0	1.104280	-2.04	69.815	30.004454	0.004454	# #	3 1.2924147E-01
32.0	1.100330	-1.92	70.014	31.998419	-0.001581	# #	4 1.4314586E+00
34.0	1.094400	-1.83	70.200	34.000298	0.000298	# #	5 -4.3404897E+00
36.0	1.093020	-1.77	70.379	35.999512	-0.000488	# #	6 3.1937273E+00
38.0	1.089510	-1.74	70.554	38.000702	0.000702	# #	7 -1.0105220E+00
40.0	1.086670	-1.72	70.726	39.999457	-0.000343	# #	8 1.1961359E-01
42.0	1.077450	-1.72	71.156	40.000625	0.000625	# #	
44.0	1.068820	-1.74	71.587	40.014240	0.014240	##### 7.1384998E+01	
46.0	1.060010	-1.78	72.028	44.991825	-0.008175	# #	
48.0	1.051080	-1.82	72.478	49.984299	-0.015701	# #	
50.0	1.041820	-1.85	72.934	64.983404	-0.014594	# #	
52.0	1.032470	-1.88	73.403	70.002525	0.002525	# #	
54.0	1.023800	-1.90	73.874	75.011948	0.011948	# #	
56.0	1.018220	-1.92	74.115	77.514586	0.014586	# #	
58.0	1.013410	-1.93	74.355	80.014743	0.014743	# #	
60.0	0.999380	-1.97	75.330	90.000557	0.000557	# #	
100.0	0.973920	-2.02	76.328	99.979088	-0.020912	# #	
110.0	0.953440	-2.07	77.351	109.986168	-0.013832	# #	0 5.0014240E+01
120.0	0.932910	-2.11	78.396	120.007729	0.007729	# #	1 1.1388309E+01
130.0	0.911280	-2.14	79.457	130.003143	0.003143	# #	2 -2.3700913E-01
140.0	0.889480	-2.18	80.535	139.999754	-0.000244	# #	3 1.7073520E-02
150.0	0.867770	-2.20	81.630	150.013824	0.013824	# #	4 -1.4151544E-03
160.0	0.845640	-2.23	82.735	159.997574	-0.002426	# #	5 1.0131003E-04
170.0	0.823250	-2.25	83.854	170.001083	0.001083	# #	6 -4.6486232E-06
180.0	0.800640	-2.27	84.982	179.991180	-0.008820	# #	7 1.1574193E-07
190.0	0.777840	-2.29	86.121	189.994822	-0.004178	# #	8 -1.1551893E-09
200.0	0.754880	-2.30	87.269	200.000931	0.000931	# #	
210.0	0.731740	-2.32	88.424	210.000703	0.000703	# #	
220.0	0.708480	-2.33	89.584	220.000874	0.000874	# #	
230.0	0.685130	-2.34	90.753	230.000817	0.000817	# #	
240.0	0.661740	-2.34	91.920	239.993042	-0.006958	# #	
250.0	0.638380	-2.35	93.088	249.997494	-0.002504	# #	
260.0	0.615120	-2.32	94.259	259.994631	-0.005369	# #	
270.0	0.592040	-2.29	95.402	270.002777	0.002777	# #	
280.0	0.569280	-2.24	96.539	279.994613	-0.005387	# #	
290.0	0.546810	-2.23	97.642	290.003967	0.003967	# #	
300.0	0.524420		98.770	299.998640	-0.001160	##### 9.8749997E+01	

Fig. 4. Typical Calibration Sheet.

catastrophically, have finite front to back resistance ratios or were obviously out of calibration upon cooldown. The source of damage was traced to the R.F. start of the heliarc welding work that followed installation. The problem should be more fully investigated but it appears that enough energy is coupled into the diode to damage the thermometer if its leads are short circuited or terminated in a low impedance. Damage is caused by either high circulating forward currents or by exceeding the reverse breakdown voltage rating of the semiconductor junction. Open circuited leads eliminates the problem but to be absolutely safe an R.F. bypass should be installed as close to the diode as possible.

c) Cryogenic thermometers at helium temperature are usually high impedance devices. By observing accepted wiring and grounding practices hum pick-up and noise can be minimized but in some areas because of poor grounds or local high power equipment, minimized hum may still be appreciable. It is therefore good practice to always use voltage to frequency or dual-slope analog to digital converters to take advantage of their ability to reject ripple.

d) Analog to digital converter ripple rejection is perfect only when positive and negative ripple envelopes are equal and average to zero. When silicon diode sensors are utilized and hum is present on the normal 10 microampere constant current drive a distorted hum voltage envelope will appear across the diode junction producing a negative D.C. error voltage. The negative offset is added to the positive junction voltage drop which produces an output signal that favors higher temperature readings. The effect is inherent in all junction devices because of their non-linear dynamic impedance around the D.C. operating point. In bench tests millivolt level offsets were generated which can correspond to errors of many tenths of degrees depending upon sensor dv/dt . The addition of a .01 μ f high quality capacitor across the diode completely eliminates the ripple and is standard on all BNL installations.

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