section. The temperature versus normalized resistance curve is shown in FIG. **26**. The dramatic change in temperature-resistance characterization led to the testing of a second generation of resistors. It is thought that these changed characteristics are caused over time by the heating of the resistors. The operation of the resistors effectively caused them to anneal themselves. Annealing changed the geography of the platinum grain boundaries and thus changed the resistivity of the resistors.

In order to avoid this effect in future testing, new resistor slides were annealed at 600° C. for 1 hour as the last step in their process. This temperature is higher than operating temperatures are likely to reach, but not so high that major agglomeration will result. Once the anneal was complete, the new resistors were characterized as described above for the first generation resistors.

First, the resistivity of the platinum at room temperature was found to be 2.056×10^{-7} Ωm, less than the unannealed resistors that were 2.41×10^{-7} Ωm. Next the resistances were measured using a multimeter, and the line widths were computed as before, as shown in Table 6.

TABLE 6

Measured resistances and computed line widths of second generation resistors.

	Resistor #	L (um)	R (Ohms)	Computed Line Width (um)	Design (um)
Slide 3	1	3000	553	13.12	6
	2	2500	481	12.57	6
	3	500	146	8.28	3
	4	1000	281	8.61	3
	5	1000	205	11.80	6
	6	2000	409	11.83	6
	7	1500	310	11.70	6
	8	1000	186	13.00	6

The temperature-resistance characteristic or the resistors was then measured on a hotplate as described above, and is shown in FIG. **27**.

At this point, the bubble formation characteristics of the resistors were tested as described previously with boiled, deionized water. Voltages were ramped up by 0.5 V steps with delay times of 1 ms using the HP4145b, as before. None of these tests resulted in residual gas bubbles since the delay time was short, and the maximum voltage used was just above the bubble nucleation voltage, determined by testing. All resulting vapor bubbles condensed back into the liquid phase within one minute of stop of current flow.

A resulting I-V curve is shown in FIG. **28**, and the corresponding temperature curve is shown in FIG. **29**. From the curve we can see that the onset of boiling occurred at about 200° C., a much lower temperature than for the first generation resistors, and well below the superheat limit of water. For the 8 second generation resistors tested, boiling points ranged from 128° C.–200° C., with the majority of the temperatures above 180° C. This suggests that the boiling is in the heterogeneous nucleation regime as discussed earlier. The cavity radii corresponding to these boiling inception temperatures are calculated from Equation (1-59).

$$r_c = \frac{2\sigma T_{sat}}{h_{fg}\rho_v(T_w - T_{sat})} \tag{1-59}$$

The results of this calculation are shown in Table 7.

TABLE 7

Bubble nucleation cavity radii corresponding to measured boiling temperatures.

Resistor #	Boiling Temperature (C)	Cavity Radius (um)
1	200.7	0.33
2	198.3	0.34
3	170.4	0.47
4	183.2	0.40
5	128	1.19
6	188	0.38
7	189	0.37
8	169	0.48

From this we can see that bubbles were nucleated in radii ranging from 0.3–1.2 μm. As discussed previously, these cavities were most likely formed during the 600° C. anneal, during which the grooves at the grain boundaries widened creating cavities.

The second generation resistors were also tested for the repeatability of their boiling temperatures. I-V curves were measured as in the previous section, and then remeasured for the same conditions several times. Between measurements, time was given for the vapor bubbles to dissipate so that the characteristic jump in the I-V curve at boiling could be observed with each measurement. The boiling point was found to be very repeatable, and an example of the results is shown in FIG. **30**. This result demonstrated the potential of a control system based on a jump in the I-V curve at the onset of boiling, since the boiling point remained fixed.

Another interesting result from this testing is that for a particular resistor, the bubbles tended to nucleate in the same locations on the resistor each time. This strengthens the hypothesis that the bubbles are nucleating in the heterogeneous regime, in cavities created by thermal grooving caused by the annealing.

Results

The cell chip was attached to the glass resistor slide as described earlier, and then tested in two ways. First tests were done with stagnant fluid on the device. Then the device was put into the flow chamber for testing. The results of these tests are described below.

For these tests, several drops of bulk solution were placed on top of the cell chip, and contained by the PDMS gasket. A drop of the polystyrene bead solution was then added to the bulk fluid and allowed to settle. The bulk solution was a 0.05% solution of Triton x-100 surfactant in deionized water. The bead solution was about 1% beads diluted in the same bulk solution. Some of the beads settled into wells, as shown in FIG. **42**. When voltage across the resistor was ramped up by the HP4145b, an I-V curve with a jump similar to that in FIG. **24** was produced, demonstrating that boiling had occurred. Consequently, the bubble formation under the well caused a volume expansion which rapidly ejected the beads from the well. First the beads are in the well, and then they are rapidly expelled. This sequence was also captured on videotape, and the process was repeated multiple times with the same success.

Preliminary dynamic testing was performed in the flow chamber. Beads were ejected in a similar way to the static test, and carried away in the flow. The preliminary tests suggested that the beads are held in the wells against a reasonable flow rate, and are ejected into the flow when a microbubble forms.