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Low-temperature conductivity behaviour of ion implanted silicon bolometers

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Abstract. Resistivity measurements carried out in the temperature range 80 mK to 1 K on silicon bolometers—phosphorous doped by ion implantation—at concentrations near the metal–insulator transition, exhibit variable range hopping (VRH) conduction in the whole observed temperature range, with a $T^{-1/2}$ dependence, in accordance with the Coulomb interaction model for low-temperature conductivity in disordered systems. Samples which apparently show a different behaviour, intermediate between VRH and metallic conduction, can be modelled by a metallic resistance in parallel with an active layer which follows the classic $\exp(T_0/T)^{1/2}$ law. The observed behaviour can be explained in terms of residual radiation damage induced by the ion implantation process.

1. Introduction

Silicon bolometers have found important applications in the fields of molecular beam spectroscopy [1] and infrared radiation measurement [2]. More recently, the Wisconsin University group, in collaboration with the Goddard Space Flight Center [3], have obtained very sensitive devices, in the range 10–20 eV, which are suitable for high-resolution cosmic x-ray spectroscopy. At this point silicon bolometers became potential candidates for the neutrino mass determination [4]. Realization, construction and proper characterization of the devices cannot omit consideration of the basic understanding of the electrical properties of the material. The present paper aims to investigate this latter aspect, in view of the peculiar ion-implantation doping technique.

The theory of electrical conductivity in disordered systems relies on Mott's original model of the metal–insulator (MI) transition [5] which predicts a relationship between resistivity and temperature of the form

$$\rho \propto \exp(T_1/T)^{1/4}$$

in the temperature range (<3–5 K) where variable range hopping (VRH) conduction occurs. Subsequently, after Pollak's work [6], Efros and Shklovskii [7] developed a

model in which the Coulomb interaction between carriers is taken into account, leading to a resistivity–temperature dependence of the form

$$\rho \propto \exp(T_2/T)^{1/2}.$$

In the previous equations, both T_1 and T_2 are constants which depend on the correlation length ξ of the impurity wavefunction. Experimental data have been reported in the literature [8] and they show a large spread in the value γ of the exponent in T^{γ}, ranging from less than 0.20 up to about 0.70, depending upon substrate type and sample preparation.

In this work we present our results concerning ion-implanted silicon bolometers aiming to redress the uncertainty about the exponent γ in the general expression

$$\rho = \rho_0 \exp(T_0/T)^{\gamma}.$$

2. Experimental procedure

Bolometers have been constructed on single crystal, Czochralski-grown p-type ⟨100⟩ silicon slices of 4 inch diameter and 0.5 mm thickness. The silicon substrate is boron-doped at a nominal concentration of $5–7 \times 10^{15}$ ions/cm^3. The thermistor is obtained by ion implantation at doses which correspond to the critical concentrations of the MI transition. They are 3.74×10^{18} cm^{-3} for Si:P [9] and 8.55×10^{18} cm^{-3} for Si:As [10]. The implantation energy was adjusted in order to have a box impurity profile, i.e. a constant concentration up to a depth of 0.5 μm. After ion implantation all samples were annealed at 920 °C for 30 min in N_2O_2. After contact opening and metal patterning, each bolometer was cut into a 1 mm × 0.5 mm dice. For more details about the technology used to construct the bolometers, the reader is referred to [11]; their performances as radiation detectors have been reported in [12].

Electrical connection with the devices was made using gold wires, which also provide the thermal link to a copper holder maintained at cryogenic temperatures inside an Oxford Instruments He^{3-4} dilution refrigerator. Resistivity measurement was performed at 30 Hz with an AC resistance bridge from Schaeffer. Total power dissipation inside the bolometer was kept below 10 pW in order to avoid any appreciable overheating. The holder temperature is monitored and controlled by means of a Lakeshore carbon–glass calibrated thermistor. Temperature accuracy was better than ±2% over all the range investigated.

An accurate determination of the dopant concentration in diffusion-doped or ingot samples has been reported to be obtained from the resistivity ratio $\rho(4.2\ \mathrm{K})/\rho(296\ \mathrm{K})$ [13].

In our case, since the implantation profile was achieved by means of multiple implants and doubly ionized ions, first a calibration of the dopant profile shape was obtained from a *C–V* plot and threshold voltage measurements. Secondly, the complete activation of the implanted dose was checked with a four-point probe and Hall effect measurements at room temperature.

In addition, owing to possible systematic errors in the ion implanter set-up dose with respect to the expected nominal concentration value, different slices were implanted with slightly different doses, ranging from completely metal samples to completely insulator samples. We are then fairly confident that the samples reported here are doped across the critical concentration and they are good representatives of the MI transition.

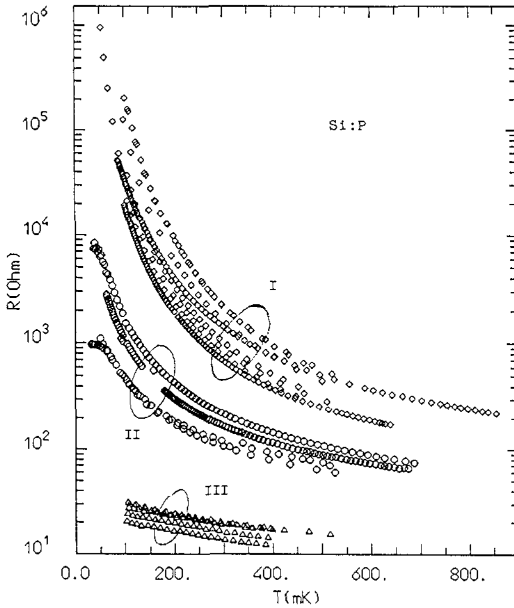

Figure 1. Resistance against temperature of Si:P samples ion implanted at the nominal critical concentration of $3.74 \times 10^{18}\ \mathrm{cm}^{-3}$.

Optimization of the ρ implantation conditions has been reported in [24]. We wish to emphasise that samples originating from the same slice are indistinguishable at room temperature in the sense that their resistivity is equal within experimental error ($\pm 1\%$).

3. Data analysis and results

The experimental data obtained from low-temperature resistivity measurements on a set of samples taken from the same slice of P-implanted silicon bolometers are reported in figure 1. The samples are nominally identical but they exhibit a remarkably different behaviour, with a resistance spread over five orders of magnitude. In spite of this, the samples are grouped in three distinct classes, which have been labeled I, II, and III. Group I samples behave like semi-insulating conductors. Group III samples exhibit a metallic-type conduction. Group II samples lie in between and show intermediate behaviour. The resistivity of group I and group II samples can be fitted with an expression of the form:

$$R = R_0 \exp(T_0/T)^s$$

where R_0, T_0, and s are adjustable fitting parameters. The aim of the fitting procedure is to determine these parameters with relatively high accuracy, with special care on the exponent s, which is supposed to be unknown *a priori*. In order to obtain reliable values of the fitting parameters we have compared the following three different methods.

(i) δR minimum. This method consists of finding the minimum of the mean relative error δR, defined as

$$\delta R = (1/n) \sum |[R_i - R_0 \exp(T_0/T_i)^s]/R_i|$$

where R_i and T_i are the experimental values, and, for each value of s, R_0 and T_0 are the

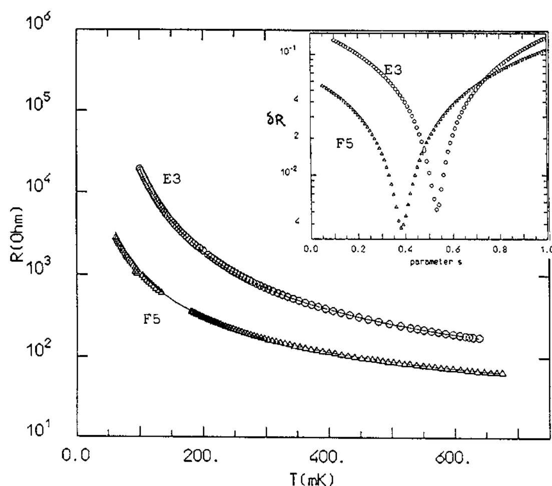

Figure 2. Two examples showing fitting accuracy of the δR minimum method. The inset shows how the parameter s is obtained from δR minimum.

best fit parameters. In this respect, s is treated as an externally fixed parameter, which in turn can be changed independently. In our case, s was incremented by steps of 0.01 ranging from 0–1. A typical result is reported in figure 2. The inset of figure 2 shows how the parameter s is determined from the δR minimum. The fitting accuracy depends on the incremental step resolution Δs, but it is practically overcome by the experimental measurement accuracy for Δs of less than 1%.

(ii) Derivative method. The performance of a bolometer is related to a parameter, called sensitivity A, defined as the logarithmic rate of change of R with T:

$$A = -\mathrm{d}(\log R)/\mathrm{d}(\log T).$$

The higher the sensitivity, the higher the responsivity of the bolometer is, i.e. the response to an external excitation. The sensitivity A is identically equivalent to the reduced energy W:

$$W = (1/T)[\mathrm{d}(\ln R)/\mathrm{d}(1/T)]$$

which represents the dimensionless activation energy in the VRH conduction regime. The derivative method consists of finding the parameter A directly from the slope of $\log(R)$ against $\log(T)$ data points. The advantages of this method is that no functional dependence is assumed *a priori*, the $\ln(A)$ against $\ln(T)$ plot defines the region where VRH occurs, and in that region the slope of the curve gives directly the parameter s ($\ln A = -s \ln T +$ constant). The disadvantage is that the derivative is very sensitive to any variation of the experimental points, and even small local fluctuations are amplified. As a consequence, this method is applicable only if the experimental data are noiseless, and they follow a well behaved, monotonic function. In any case, the values of A obtained are rather scattered and their least square fit usually gives a poor correlation coefficient. In our case the point derivative of $\log(R)$ against $\log(T)$ has been evaluated from the incremental ratio of three adjacent points. This procedure excludes the first and last data point.

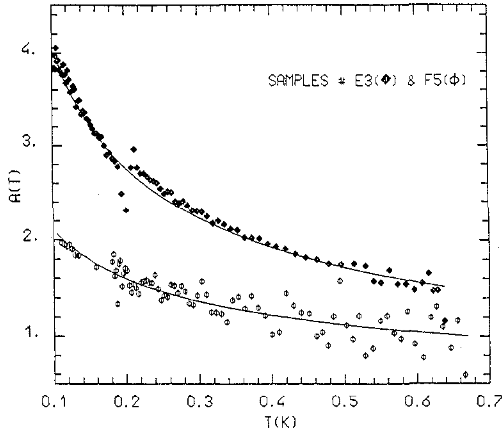

Figure 3. Sensitivity $A(T)$ against temperature as obtained from two different methods. Points, derivative method; full curve, polynomial fit.

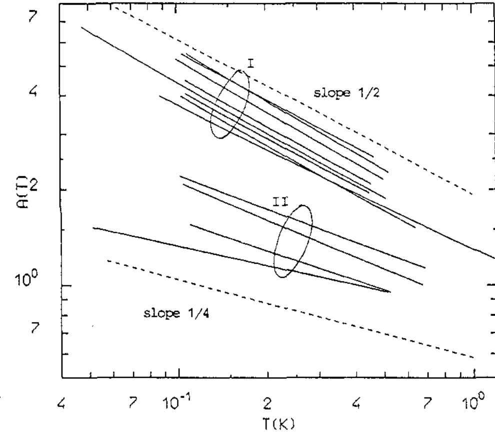

Figure 4. Log–log plot of sensitivity $A(T)$ against temperature of group I and group II samples.

(iii) Polynomial fit. In order to overcome the above mentioned drawback, we have carried out a polynomial fit of the expression log(log R) against (log T) assuming a functional dependence of the form

$$\log(\log R) = a + b(\log T) + c(\log T)^2 + \ldots$$

from which we have

$$\mathrm{d}(\log R)/\mathrm{d}(\log T) = \log R[b + 2c(\log T) + \ldots] = -A.$$

The advantage of this method is that the log(log) function acts as a data smoothing and therefore the interpolation is much less sensitive to local fluctuations. The result is shown in figure 3. The full curve represents the second-order polynomial fit, while the points represent values obtained from the derivative method. Notice that the polynomial fit looks very like the best fit line through the dotted points.

In table 1 the values of R_0, T_0, and s obtained from the three different methods are reported for comparison, along with their relative per cent errors ($\delta R\%$). As can be seen, the three methods are consistent with each other. Moreover, group I samples show a T^{-s} dependence with an exponent equal to 0.52 ± 0.03, while group II samples show a T^{-s} dependence with s ranging from 0.21 to 0.39. Such deviations from the expected theoretical values of the exponent in the VRH conduction regime have already been observed in doped semiconductors [14], especially at low temperatures.

In figure 4 we have plotted log(A) against log(T) along with the theoretical slopes 0.5 and 0.25 superposed for comparison. Group I and group II samples show an almost linear dependence in the whole temperature range, confirming that they show VRH conduction. Group III samples do not follow an $\exp(T_0/T)^s$ law. They are very close to the MI transition, and therefore we have tried a fit of the form

$$\sigma = \sigma(0) + mT^{\beta}$$

where $\sigma(0)$ is the zero-temperature conductivity. In the mainframe of localization theory [15] we expect a positive correction of the $\sigma(0)$ conductivity with exponent $\beta = 1$, while

Table 1. Fitting parameters R_0, T_0, and s obtained from $R = R_0 \exp(T_0/T)^s$ with three different methods: (i) δR min; (ii) derivative (3PTS); (iii) polynomial fit (POL).

	s			T_0 (K)			R_0 (Ω)			δR (%)		
Sample	δR	3PTS	POL	δR	3PTS	POL	δR	3PTS	POL	δR	3PTS	POL
E1	0.53	0.55	0.53	5.93	4.97	6.05	8.09	9.73	7.88	1.04	1.09	1.04
E2	0.56	0.57	0.56	6.25	5.51	6.24	9.46	10.8	9.42	0.96	1.23	0.99
E3	0.53	0.54	0.53	4.54	3.92	4.62	10.2	11.8	10.0	0.52	0.67	0.56
E4	0.56	0.56	0.55	5.41	5.32	5.86	10.4	10.5	9.40	0.90	1.01	0.88
E5	0.53	0.52	0.51	8.58	9.29	10.1	6.06	5.60	4.93	1.48	1.73	1.47
F4	0.54	0.52	0.54	4.90	5.87	5.04	9.76	8.32	9.28	2.59	4.25	2.78
F6	0.51	0.52	0.51	6.14	5.24	6.20	7.31	8.53	7.21	0.85	0.93	0.87
N5	0.46	0.43	0.46	9.27	13.3	9.80	11.4	9.86	10.7	2.64	7.92	2.55
F3	0.36	0.33	0.35	15.9	27.8	20.2	3.37	2.44	2.90	0.84	1.11	0.85
F5	0.38	0.49	0.38	8.71	2.24	7.83	4.60	11.3	4.90	0.37	2.34	0.38
N7	0.24	0.25	0.21	133	553	797	1.63	2.98	0.74	2.99	6.25	3.04
H14	0.31	0.33	0.31	19.5	12.6	18.3	2.78	3.47	2.87	0.43	0.49	0.42

Table 2. $\sigma = \sigma(0) + mT^{\beta}$.

Sample	$\sigma(0)$ (Ω^{-1} cm^{-1})	m	β	$\delta\beta$ (%)
1H	1.50	9.13	0.65	2.55
2H	2.76	7.78	0.81	2.45
3H	4.00	13.3	1.32	3.86
4H	4.54	14.1	1.19	3.85
19H	1.50	8.62	0.65	1.58

Coulomb interaction theory of disordered metals [16] gives $\beta = \frac{1}{2}$ and a magnitude m which can change sign crossing the MI transition, depending on whether the Hartree term or the exchange term dominates in the electron–electron interaction matrix. The result of fitting the experimental data with m and β as free parameters is reported in table 2. The δR method has been applied, with β ranging from 0–2 in steps of 0.01. We have also verified that the metallic fit is not applicable to group II samples. In fact, in that case we obtain negative or null values of $\sigma(0)$.

The $\sigma(0)$ conductivity is estimated taking into account the geometrical factors of the conductive layer. They are $W = 2700$ μm (width), $L = 15$ μm (length), and $x_j = 0.5$ μm (depth). The conversion factor is estimated to be 0.01 cm.

From inspection of table 2 we can point out two main considerations. Firstly, the values of m are positive and secondly, the ratio $\sigma(0)/\sigma_M$ (σ_M is Mott's minimum metallic conductivity [17], $\sigma_M = 20\ \Omega^{-1}$ cm^{-1} for Si : P) ranges from 0.2–0.07. The corresponding values of β lie between 1.14 and 0.62 respectively. These values are not in contrast with those reported by Rosenbaum *et al* [9] who found $\beta = 2$ for $\sigma(0)/\sigma_M < 0.1$, suggesting that the form $\sigma = \sigma(0) + mT^{\beta}$ may not be adequate to model the conductivity behaviour of samples very close to the MI transition with a positive correction to the $\sigma(0)$ conductivity.

Table 3. Corrected values of conductance of group I and II samples with $\sigma = \sigma_m + 1/R_0 \exp - (T_0/T)^{1/2}$.

Sample	$\sigma_m\ (\Omega^{-1})$	T_0 (K)	$R_0\ (\Omega)$
E1–N5	$<10^{-6}$	6.90 ± 1.9	8.3 ± 1.8
F3	2.27×10^{-4}	3.13 (20.2)	9.12 (2.90)
F5	2.28×10^{-4}	2.48 (7.83)	9.80 (5.01)
B7	5.87×10^{-4}	1.46 (797)	14.2 (0.74)
B14	7.47×10^{-4}	1.82 (18.3)	9.83 (2.87)

Let us now reconsider the group II samples. They lie in between the 'well behaved' group I samples, which exhibit VRH conduction with exponent 0.5, as for the Coulomb interaction model, and the 'metal-like' group III samples, which exhibit a zero-temperature finite conductivity.

We have supposed that for those samples which show an intermediate behaviour the electrical conduction is due to the superposition of two effects: VRH with exponent 0.5, and metallic conduction through narrow channels with very small cross sections. The combination of the two effects can be expressed as:

$$\sigma = \sigma_m + (1/R_0) \exp - (T_0/T)^{0.5}$$

where the metallic term σ_m must be quite small, but not less than $10^{-6}\ \Omega^{-1}$, i.e. the intrinsic resolution of our measurement system. The results of the best fit obtained from the δR method, with σ_m now ranging as a free parameter from 0 to $1/R_{max}$, are reported in table 3. The values in parentheses are taken from table 1 and have been repeated here for comparison. Only samples belonging to group II have a significant σ_m contribution, as expected. The values of T_0 obtained from table 3 are compared with the theoretical value of T_0 given by the Coulomb interaction model [18]:

$$T_0' = Be^2/\kappa a \simeq 1500\ \mathrm{K}$$

where B is a numerical coefficient (=2.9), e is the electronic charge, κ is the static dielectric constant (=12.94 pF cm^{-1} for Si), and a is the characteristic decay length of the impurity wavefunction (=26 Å for Si:P from Sasaki [19]). In accordance with the scaling theory of localization [15], both the impurity radius a and the dielectric permittivity κ diverge near the MI transition as $(1 - N/N_c)^{\nu,\eta}$ where ν, η are critical exponents—$\nu = -0.55$ and $\eta = -1.15$ [9] for a and κ respectively. We then expect a reduction of T_0, scaling down as N approaches the critical concentration N_c, as

$$T_0 = T_0'(1 - N/N_c)^n$$

with n, the critical exponent, equal to $-(\nu + \eta) = 1.7$. In this respect, the percentage deviation of the P concentration from the critical value of 3.74×10^{18} cm^{-3} is estimated to be 4–5% for group I samples, and 1.7–2.6% for group II samples. These values are significantly higher than expected from the process control parameters. In fact, ion implantation uniformity is specified to be better than 2%, and all the samples have experienced the same annealing cycle simultaneously. In spite of this, a local deviation of more than 2% occurs which can be accounted for by clustering of defects, as well as

impurities, during the annealing cycle. In fact, dopant clustering is likely to produce metallic droplets inside the crystal matrix, while clustering of defects induces acceptor states in the band gap of silicon, which in turn correspond to a local enhancement of the compensation ratio. Another contribution to local non-uniformity could be due to a non-uniform depth impurity distribution. This occurrence was carefully checked and avoided during ion implantation by an accurate control of the beam purity.

4. Discussion

The junction depth of a silicon sample doped by ion implantation is determined primarily by the ion energy, and, for practical purposes, is limited to about 0.5 μm. In the VRH conduction regime the hopping length grows as T^{-s}, with $s = \frac{1}{2}$ in the Shklovskii–Efros (SE) model, or $s = \frac{1}{4}$ in Mott's model. Therefore the question arises whether the conductivity of shallow-doped samples might become two-dimensional below a certain temperature. In the SE theory a change from three- to two-dimensional conduction does not affect the exponential factor significantly, while in the Mott model the conductivity is expected to behave as $\exp(T_0/T)^{1/3}$. This could justify the behaviour of group II samples, with an exponent close to 0.3.

An estimate of the mean distance between hopping sites, R_{ij}, in the mainframe of the SE model, i.e.. in the worst case for the R_{ij} divergence, is carried out assuming that the density of states (DOS) vanishes at the Fermi level as:

$$g(\varepsilon) = \alpha\kappa^3/e^6\varepsilon^2$$

where α is a numerical coefficient ($\alpha = 3/\pi$), κ is the dielectric permittivity of silicon and e is the electronic charge. The total number of states in a band of width ε_0 is:

$$N(\varepsilon_0) = \int_{\mu-\varepsilon_0}^{\mu+\varepsilon_0} g(\varepsilon)\,\mathrm{d}\varepsilon = \frac{2}{3}\alpha\frac{\kappa^3}{e^6}\varepsilon_0^3.$$

The hopping resistivity can be written in the form:

$$\rho = \rho_0 \exp\left(\frac{2}{N^{1/3}(\varepsilon)\xi} + \frac{\varepsilon}{k_{\mathrm{B}}T}\right)$$

where T is the absolute temperature, k_{B} is the Boltzmann constant, ξ is the characteristic decay length of the impurity wavefunction, and $N^{-1/3}(\varepsilon)$ represents the mean distance between hopping sites. The first term of the exponential expresses the contribution of the quantum tunnelling between partial overlapping electronic wavefunctions. The second term is the Boltzmann factor $\exp(\varepsilon/k_{\mathrm{B}}T)$ of the jumping probability between two states having an energy difference ε.

The Mott criterion of the optimum band width $\varepsilon_0(T)$ says that the resistivity has a minimum for $\varepsilon = \varepsilon_0(T) = 2k_{\mathrm{B}}T/N^{1/3}(\varepsilon_0)\xi$. From the above conditions we have:

$$\varepsilon_0(T) = \left[2\frac{k_{\mathrm{B}}}{\xi}\left(\frac{\pi}{2}\right)^{1/3}\frac{e^2}{\kappa}\right]^{1/2} T^{1/2}.$$

As already mentioned, both the correlation length ξ and the dielectric permittivity κ diverge as N approaches N_c. However, assuming $\xi = a = 26$ Å, and $\kappa = 12.94$ pF cm^{-1}, we can estimate an upper bound limit for the band width of $3.0 \times T^{1/2}$ meV, to which corresponds a density of states $g(\varepsilon_0) = 4.8 \times 10^{18} \times T$ eV^{-1} cm^{-3}. This latter value is

two orders of magnitude less than the free electron model density of states. For the hopping length R_{ij} we have an upper bound limit of

$$R_{ij}(\varepsilon_0) = N(\varepsilon_0)^{-1/3} = 460T^{-1/2}\ (\text{Å})$$

(for Si : As, with $a = 16$ Å, we have $R_{ij} = 370T^{-1/2}$ Å). Although this is a rough estimation of the hopping length, the result suggests that we should not be concerned with two-dimensional effects.

The Coulomb interaction model of SE predicts a decrease of the DOS near the Fermi energy, and the opening of a so-called 'Coulomb gap' at low temperatures. The fact that we observe a $T^{-1/2}$ dependence of the resistance in the whole temperature range implies that the Coulomb interaction is dominant up to 1 K. On the other hand, one necessary condition for the manifestation of the Coulomb gap in doped semiconductors is the presence of some degree of compensation. In our samples the original compensation factor K is of the order of 10^{-3}, but, because of the doping process by ion implantation, we can expect an increase of the actual compensation factor due to the introduction of crystal defects with energy levels located in mid-gap. Radiation damage induced defects are only partly recovered by the annealing cycle [20]. Agglomeration of defects, especially vacancies and interstitials, most likely occurs in the form of dislocation loops [21, 22]. Crystal defects are electrically inactive at room temperature because their energy is much higher than the impurity ionization energy. However, their presence can increase the electron–hole (e–h) generation–recombination rate in p–n junctions, and then give rise to leakage currents in reverse biased diodes. At low temperatures they can act as acceptor centres for the impurity band. The density of states at the Fermi level in the absence of the Coulomb gap is

$$g_0(\mu) = KN_D/\varepsilon_D$$

where K is the ratio between acceptor and donor centres, N_D is the donor concentration, and ε_D is the interaction energy between adjacent donor sites given by

$$\varepsilon_D = e^2 N_D^{1/3} \kappa^{-1}.$$

Assuming $g_0(\mu)$ equal to $g(\varepsilon_0)$, we have $K = 0.025$ (2.5%). That is the minimum value required in order to observe a Coulomb gap in our experimental conditions. This value can rise up to 25% if the divergence of the dielectric permittivity is taken into account [23].

5. Summary and conclusions

In this work we have examined the conductivity behaviour of phosphorus-implanted silicon bolometers in the VRH regime where the $\exp(T_0/T)^s$ law holds. A new method to extract the parameter s from the d(log R) against d(log T) plot has been presented, and its validity checked against two other fitting methods. The experimental data are in agreement with the Shklovskii–Efros model of conductivity in disordered systems, which predicts the opening of a Coulomb gap in the density of states of the impurity band. P-implanted silicon bolometers behave like compensated semiconductors. The manifestation of the Coulomb gap is thought to be due to the presence of residual defects left after partial recovery of the implantation damage. Such defects act as acceptor centres at low temperatures. Their presence can also justify the observed local dishomogeneities in the low-temperature resistivity. The samples which exhibit intermediate behaviour

between metal-like and insulating semiconductors, can be modelled with a shunt resistance in parallel with an active layer following the classic $\exp(T_0/T)^{1/2}$ law. This indicates that both the insulator and the metal phase can coexist in non-homogeneous samples, and then induce erroneous results if the two components cannot be discriminated.

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References

[1] Boschetti A, Zen M, Bassi D and Scotoni M 1984 *Chem. Phys.* **87** 131
[2] Downey P M, Jeffries A D, Meyer S S, Weiss R, Bachner F J, Donnelly J P, Lindley W T, Mountain R W and Silversmith D J 1984 *Appl. Opt.* **23** 910
[3] McCammon D, Juda M, Zhang J, Holt S S, Kelley R L, Moseley S H and Szymkowiak A E 1987 *Proc. 18th Int. Conf. on Low Temperature Physics (Kyoto, Japan, 1987); Japan. J. Appl. Phys.* **26** suppl 26-3
[4] Alessandrello A, Camin D V, Fiorini E, Giuliani A, Buraschi M I and Pignatel G U 1989 *Nucl. Instrum. Methods* A**279** 142
[5] Mott N F 1968 *J. Non-Cryst. Solids* **1** 1
[6] Pollak M 1970 *Discuss. Faraday Soc.* **50** 13
[7] Efros A L and Shklovskii B I 1975 *J. Phys. C: Solid State Phys.* **8** L49
[8] Maggiani F 1988 *Thesis* University of Genova, Italy (Review of experimental data)
[9] Rosenbaum T F, Milligan R F, Paalanen M A, Thomas G A, Bhatt R N and Lin W 1983 *Phys. Rev.* B **27** 7509
[10] Shafarman W N and Castner T G 1986 *Phys. Rev.* B **33** 3570
[11] Buraschi M I and Pignatel G U 1989 *Proc. 2nd E-MRS Conf. on Superconducting and Low-Temperature Particle Detectors* ed G Waysand (New York: Elsevier) pp 241–250
[12] Alessandrello A, Camin D V, Fiorini E, Giuliani A, Buraschi M I and Pignatel G U 1988 *Nucl. Instrum. Methods* B **31** 462
[13] Rosenbaum T F, Andres K and Thomas G A 1980 *Solid State Commun.* **35** 663
[14] Kobayashi S, Mondeb Y and Sasaki W 1979 *Solid State Commun.* **30** 661
[15] Abrahams E, Anderson P W, Licciardello D C and Ramakrishnan G V 1979 *Phys. Rev. Lett.* **42** 673
[16] Altshuler B L and Aronov A G 1979 *Sov. Phys.–JETP* **50** 968
[17] Mott N F 1972 *Phil. Mag.* **26** 1015
[18] Shklovskii B I and Efros A L 1984 *Electronic Properties of Doped Semiconductors* (Berlin: Springer)
[19] Sasaki W 1985 *Phil. Mag.* B **52** 427
[20] Servidori M, Angelucci R, Cembali F, Negrini P, Solmi S, Waumseil P and Winter U 1987 *J. Appl. Phys.* **61** 1834
[21] Gibbons J F 1971 *Ion Implantation* ed F H Eisen and L T Chadderton (New York: Gordon and Breach) pp 343–348
[22] Mader S 1984 *Ion Implantation—Science and Technology* ed J F Ziegler (New York: Academic) pp 109–138
[23] Sanguinetti S, Pignatel G U and Buraschi M I to be published
[24] Baciocco E, Boragno C, Valbusa U, Bresolin C and Pignatel G 1988 *Proc. 17th Eur. Solid State Device Research Conf., ESSDERC '87 (Bologna, Italy, 1987)* ed G Soncini and P U Calzolan (Amsterdam: North Holland) p. 515